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A study of the kinematics of ingress and egress of upright and recumbent seats

Christopher Moore[a], Ashish Nimbarte[a], Sudhakar Rajulu[b], and Fereydoun Aghazadeh[c]
[a]*Industrial and Management Systems Engineering, West Virginia University, PO Box 6070, Morgantown, WV, USA*
[b]*Anthropometry and Biomechanics Facility, Johnson Space Center, NASA, 2101 NASA Rd 1, Houston, TX, USA*
[c]*Department of Construction Management & Industrial Engineering, Louisiana State University, 3132 - B Patrick F. Taylor Hall, Baton Rouge, LA, USA*

Abstract. Research has been done on the maximum reach and ingress/egress of upright seats. However, research on recumbent seats and comparisons between recumbent and upright seats is limited. By using an eight-camera Vicon motion capture system and C-motion Visual 3D modeling software, this research compared the ingress/egress joint kinematics and maximal planar reach of an upright seat with a recumbent seat. Mean range of motion and mean peak angle for each ingress/egress task were determined and the values for the upright seat were compared to the values for the recumbent seat. For each reach task, three extreme points were extracted and compared between the upright and recumbent seat. Seat orientation was found to have a statistically significant effect on the range of motion of several joints during the ingress/egress tasks, as well as one of the extreme points during the reaching tasks.

Keywords: ingress, egress, recumbent seat, 3D kinematics, planer reach

1. Introduction

Most seats that are currently used are positioned upright. Because of the widespread use of upright seats, there has been extensive research done on them. However, recumbent seats have several applications, including confined space work, space shuttle cabins, and bicycles. Despite having such specific applications, research on recumbent seats is rather limited

1.1. Ingress/egress literature

The majority of ingress/egress research focuses on of automobile seats. Giacomin et al. (1997) analyzed the subjective comfort ratings when entering and exiting the rear seat of a vehicle. In this study, a VHS recorder and a motion measurement system were used in combination with a questionnaire to determine which design factors influenced comfort ratings the most. Loczi et al. (1993) completed research assessing the ergonomics of exiting a vehicle. This research used 3-D digitizing software to examine the affects of changing the seat height, door height, and seat position on joint kinematics. The results of the study showed that seat height and door height significantly affect a number of ingress and egress kinematic and kinetic parameters. More recently, Ait El Menceur et al. (2008) examined alternative techniques and movements used in entering and exiting vehicles by the young and elderly with prostheses. Two main families of ingress and egress movement were identified: one-foot ingress (or egress) movements in which the subject balanced in the left foot, and two-foot ingress (or egress) movements in which both feet were used. No specific difference in the ingress and egress strategies with respect to the population difference i.e. young able-bodied people, elderly or disabled people were found.

Loczi et al. also developed and evaluated RAMSIS, a 3-D CAD human model for ergonomic evaluation of vehicles, and used the model to evaluate cab design of heavy trucks (1999, 2000). RAMSIS is able to accurately predict posture and position in a vehicle CAD environment. However, nature of the analysis done by is RAMSIS purely static environments and does not provide quantitative information on the ingress/egress kinematics.

In all of these studies, the seat is in an upright orientation. In addition to understanding ingress/egress of seats, it's critical to know the effect of different seat configurations on the reach envelope of users, especially situations where they deal with a number of controls.

1.2. Reach envelope literature

Although many studies have been done on the human reach envelope, the majority of these studies focus on new methods of determining, calculating, or defining the reach envelope. There are two general methods to determine the reach envelope: 1) mathematical modeling, and 2) experimental determination. A 9 degree-of-freedom model of the reach envelope based on anatomy, kinesiology, and the anatomical barriers to arm movement was formulated by Yang et al. (2005). Deisinger (2000) used ERGONAUT software to model the reach envelope based on human body limitations and anthropometric dimensions. He further claimed that ERGONAUT software is fairly accurate for practical use (Deisinger, 2000).

Although software and modeling can be used to fairly accurately determine the reach envelope based on body dimensions, there are several factors such as flexibility, posture, environmental constraints, etc. that are not taken into account by these methods. When a more accurate determination of the reach envelope is necessary, experimental methods are known to provide a better estimate. Several experimental methods have been successfully used to determine the reach envelope. Das et al. (1994) developed a method of three dimensional tracking using a stylus attached to four potentiometers through pulleys. The change in voltages in the potentiometers could be used to calculate the location of the stylus in three-dimensional space. Das et al. (2000) used this method to determine the reach envelope for seated and standing industrial workers by having participants hold the stylus while moving through the full range of motion. Reed et al. (2003) used a mechanical device that moved a button into 216 different locations in the area around the participant. While sitting in a simulated automobile cabin, consisting of a seat and a steering wheel, the participants attempted to press the button while it was in each location. The participants rated each target from 1-10 based on ease of reach and comfort. Targets that were unreachable were rated 11. This allowed the researchers to create a maximal reach envelope as well as reach envelopes based on the level of comfort and ease. In another study, Das and Sengupta (2000) compared and quantified the sitting and standing reach envelope for males and females by using a computerized potentiometric measurement system. The standing reach envelope was found to be significantly larger than the sitting reach envelope. However, only an upright seat was used in this research.

As noted, most of the existing research that deals with seat ingress/egress and the reach envelope mainly focuses on seats in an upright position. Currently, the effect of a recumbent seat configuration on ingress/egress strategies and reach envelope is not well understood. Therefore, the purpose of this study was to evaluate the effect of recumbent seat configuration on the ingress/egress joint kinematics and maximal planar reach by comparing it with an upright seat configuration.

2. Methods

2.1. Equipment

The following equipment was used in this study:

- Custom-built upright and recumbent seat platforms (Figure 1). The seats are adjustable, but only a 90° seat angle was used in this research. The upright seat included a strap to secure the upper body to the seat during the reach tasks.
- Eight-camera motion-capture system (Vicon Motion Systems, Oxford, UK). The eight cameras emit infrared light which reflects off of small retro-reflective markers. The cameras capture the reflected light and record the location of the markers in 3D space.
- Vicon Nexus 1.5.1 Software (Vicon Motion Systems, Oxford, UK). This software works with the camera system to capture the locations of the markers. The software is also used to label the marker data and can be used to analyze the data.
- C-Motion Visual3D 4.0 Software (C-Motion, Inc., Germantown, MD, USA) This software was used to formulate a dynamic model to further process the raw marker data collected using the Vicon system. Visual3D outputs kinematic data, such as joint angles, forces, and moments, that is calculated from the model.
- Custom marker set using 58 retro-reflective markers (Figure 2). This marker set was designed for

use with the Visual3D software specifically for our application.

Figure 1. Custom seat platforms

2.2. Subjects

Eight healthy male subjects were recruited for this research. Subjects were free from musculoskeletal disorders or any other condition that could limit their ability to ingress/egress or diminish their ability to reach. All subjects were made aware of the study procedures and signed IRB-approved consent forms before any study tasks took place.

Figure 2. marker-set used in this study.

2.3. Subjects

Eight healthy male subjects were recruited for this research. Subjects were free from musculoskeletal disorders or any other condition that could limit their ability to ingress/egress or diminish their ability to reach. All subjects were made aware of the study procedures and signed IRB-approved consent forms before any study tasks took place.

2.4. Subject preparation

After the subjects were informed of the study procedures and signed consent forms, the subject's height and weight were recorded. The subject then changed into elastane (Spandex) t shirt andshorts and the marker set was applied using double-sided tape.

2.5. Experimental tasks

Each subject completed two types of tasks: ingress/egress tasks and maximal planar reaching tasks. Each set of tasks is completed with the seat in the upright and recumbent positions with a 90° seat angle.

2.5.1. Ingress/egress tasks

Each subject completed three ingress and egress trials in each of the seat orientations, resulting in 36 dynamic trials. Ingress into the recumbent seat was done using the following progression.

1. Begin by laying supine on the platform to the left of the seat with legs straight and hands on the abdomen.

2. Flex the left knee, place left foot flat on platform, and place right hand across the seat.

3. Using the left foot and both hands, lift the upper body and pelvis off of the platform.

4. Lift right leg over the front of the seat and move pelvis over the seat.

5. Lower the body into the seat and bring the left leg over the front of the seat.

6. Place hands back on the abdomen.

Egress from the recumbent seat follows the reverse of this progression, and ends with the subject laying supine on the platform with the hands on the abdomen.

Ingress from the upright seat was done by beginning with the subject standing up straight to the left of the seat with the hands on the abdomen. The subject then entered the seat by moving the right leg in front of the seat, moving the left leg over beside the right leg, and then sitting into the seat and placing the hands on the abdomen. Egress followed the reverse of this progression, ending with the subject standing to the left of the seat with hands on the abdomen.

2.5.2. Maximal planar reach tasks

Each subject completed three trials per arm of each of the three planar reach tasks (sagittal, transverse, and frontal) in both seat orientations, resulting in 36 dynamic trials. While sitting in the seat, the subject was instructed to move their fully-extended arm through the complete range of motion in one of the three anatomical planes.

2.6. Data processing

2.6.1. Ingress/egress data

The ingress/egress data was processed in Vicon Nexus and the marker data was exported in C3D format. The C3D file containing the frame-by-frame marker data was imported into C-Motion Visual3D software. This data was used to create a kinematic model of each dynamic trial.

Once the kinematic model was created, the Visual3D software was used to export frame-by-frame joint angles of the right hip, left hip, right knee, left knee, and trunk. For each trial, the joint angle data was resampled to 100 data points using a resampling algorithm. The range of motion (ROM) for each joint was found by calculating the difference between the maximal and minimal joint angles attained in each trial. The peak joint angles for each trial were also recorded.

2.6.2. Maximal planar reach data

The planar reach data was processed in Vicon Nexus and Microsoft Excel. Frame-by-frame marker data was exported from Vicon Nexus in CSV file format. CSV files were imported into Microsoft Excel. The marker locations were transformed such that the clavicle marker became the origin of the coordinate frame. In each reach trial, the movement of the arm was along two axes in one plane. For each transformed trial, the coordinates for the finger marker were recorded and transformed so that a plot of the "moving axes" coordinates formed a parabola that opened downward, with the starting position on the left. (Fig. 3)

Three significant points from each trial were then extracted: the maximal value along the horizontal axis (Max-X), the minimal value along the horizontal axis (Min-X), and the maximal value along the vertical axis (Max-Y).

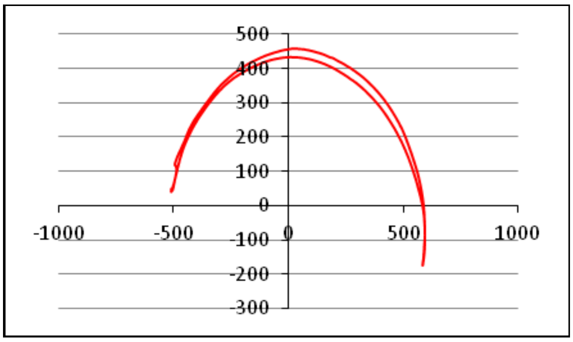

Figure 3. Exemplar plot of "moving axes" for a reaching task.

2.7. Statistical analysis

The effect of seat orientation on maximal planar reach and ingress/egress joint kinematics were evaluated using the following linear models. Due to the differences in individual fitness levels and abilities of the participants, the participants were treated as blocks.

Very similar linear models were used for the analysis of the ingress/egress data (Eq. 1) and the reach data (Eq. 2).

$$yD_{ijl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_l + \epsilon_{ijl} \quad \begin{cases} i = 1,2 \\ j = 1,2 \\ l = 1,\dots,8 \end{cases} \quad \text{(Eq. 1)}$$

$$yD_{ijl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_l + \epsilon_{ijl} \quad \begin{cases} i = 1,2 \\ j = 1,2,3 \\ l = 1,\dots,8 \end{cases} \quad \text{(Eq. 2)}$$

yD represents the dependent variables. For the ingress/egress analysis, the dependent variables were the peak angle and range of motion of the left knee, right knee, left hip, right hip, and trunk. The three dependent variables for the reach analysis were the Max-X, Min-X, and Max-Y values.

μ is the overall mean to all tasks for both the ingress/egress analysis and the reach analysis.

α_i is the effect of seat orientation. The two levels of this factor represent upright and recumbent seat orientation, therefore $i = 1, 2$.

B_j is the effect of types of tasks. The two levels of this factor for the ingress/egress analysis represent ingress tasks and egress tasks, therefore $j = 1, 2$. The three levels of this factor for the reach analysis represent the frontal, sagittal, and transverse planes.

γ_l is the effect of subjects (block effect), l = 1, …, 8.

ϵ_{ijl} is a random error term.Seat orientation and type of task are treated as fixed factors. It is assumed that each factor and two-way interaction have no effect on the dependent variables, i.e.

$$\sum_{i=1}^{2} \alpha_i = 0, \quad \sum_{j=1}^{2} \beta_j = 0, \quad \sum_{i=1}^{2}\sum_{j=1}^{2} (\alpha\beta)_{ij} = 0$$

Subjects (γ_l) are treated as a random factor and it is assumed that it is NID (0, σ_γ^2) random variable. Random error and ϵ_{ijl} follows NID (0, σ^2). In this study, the Type I error $\alpha = 0.05$ and Power of the test $(1-\beta) = 0.90$ were chosen for the hypothesis test.

3. Results

3.1. Ingress/egress joint angles

The mean and standard deviation of the range-of-motion and peak angle for the five joints are shown in Fig. 4. Seat orientation had a significant effect on the ROM of right knee (P = 0.017), right hip (P = 0.003), and trunk (P < 0.001) joints. When compared between ingress and egress tasks, in general, a higher ROM was observed during the ingress task. However, a significant effect was only observed for the ROM of the trunk joint. (P = 0.03).

Peak joint angles were found to be consistently higher for the recumbent seat configuration. A significant effect was only observed for the left knee (P = 0.016). Between task comparison showed higher peak joint angles during ingress than egress. However, statistical significance was only observed for the left knee joint (P = 0.014).

3.2. Maximal planar reach

Table 1 shows the mean and standard deviation of the maximal planar reach in the three anatomical planes. Overall, reach capacity appears to be greatest in the transverse plane at shoulder level. No associations or trends were found between the two seat orientations or the left or right arm. The seat orientation only had a statistically significant affect on the 'Max-Y' reach value of the right arm (P = 0.027).

4. Discussion

This study was aimed at evaluating ingress/egress kinematics and reach envelopes associated with a recumbent seat by comparing it with an upright seat. The results showed that the ingress/egress joint kinematics varied significantly between the two seat orientations. Peak angles were consistently higher for the recumbent seat and, with the exception of the left hip, the ROMs were also consistently higher. Surprising no difference in the reach envelop between the two seat configuration was found. In the recumbent position, a reduction in the reach envelop due to the effect of gravity was expected. A probable explanation for this observation is that the torso was secured to the seat during reaching tasks performed in upright seating. The stabilization of the truck with respect to seat may have compensated for the effect of gravity in the upright posture leading to almost similar levels of reach envelopes between the two seat orientations.

This research shows that ingress/egress of a recumbent seat requires higher rotations of the hip, knees, and trunk joints compared to an upright seat. Higher joint exertions are known to have an effect on muscle activation, which is likely to have implications regarding fatigue, strain, and musculoskeletal disorders, especially in cases where repeated ingress/egress is necessary.

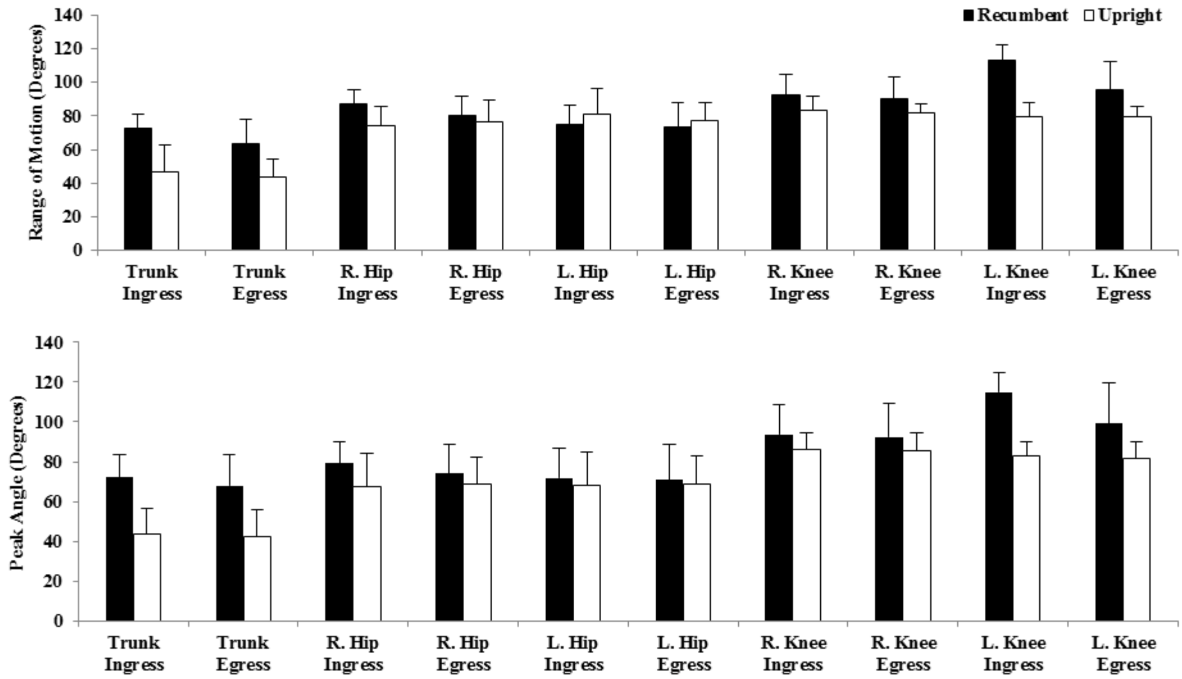

Figure 4. Mean (SD) peak joint angles and range of motion during ingress-egress tasks performed using recumbent and upright seat configurations

Transverse

Seat	Arm	Min X	Max X	Max Y
Upright	Left	-768.13 (45.20)	587.30 (157.21)	768.44 (14.44)
Upright	Right	-769.43 (37.00)	634.53 (39.50)	769.30 (40.11)
Recumb.	Left	-773.15 (38.98)	639.61 (53.08)	767.57 (31.37)
Recumb.	Right	-787.84 (44.75)	638.05 (77.26)	781.55 (39.84)

Sagittal

Seat	Arm	Min X	Max X	Max Y
Upright	Left	-555.97 (62.19)	633.92 (40.16)	530.22 (41.85)
Upright	Right	-575.72 (79.05)	625.26 (35.90)	516.31 (37.86)
Recumb.	Left	-571.73 (50.47)	613.50 (71.66)	525.38 (43.23)
Recumb.	Right	-586.91 (60.55)	610.33 (56.31)	588.25 (99.26)

Frontal

Seat	Arm	Min X	Max X	Max Y
Upright	Left	-576.29 (37.13)	340.01 (59.15)	552.03 (39.82)
Upright	Right	-592.52 (38.52)	333.23 (57.99)	549.40 (27.46)
Recumb.	Left	-578.94 (50.68)	344.29 (91.25)	524.13 (40.25)
Recumb.	Right	-572.80 (65.96)	379.54 (49.18)	552.99 (39.56)

Table 1. Mean (SD) of the maximal planar reach in different anatomical planes for recumbent and upright seat configurations.

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