Modeling Foot Trajectories for Heavy Truck Ingress Simulation

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ABSTRACT

Digital human figure models are a useful tool for simulation of driver ingress and egress for passenger cars, light trucks, and heavy commercial trucks. Simulation allows evaluation of the suitability of steps and handholds as a system. Accurate simulation requires detailed, validated algorithms to predict driver motions. One critical component of such an algorithm is the accurate prediction of foot trajectories. This paper presents an approach to foot trajectory simulation based on statistical analysis of driver motions from a laboratory study. The movements of 20 truck drivers were recorded as they entered a reconfigurable truck mockup. The foot trajectories were parameterized using Bézier curves, which accurately represent the important characteristics of the trajectories with relatively few parameters. Statistical analysis of the fitted parameters showed that the shapes of the trajectories, after normalizing for overall displacement, were independent of truck step configuration but affected by driver characteristics. The resulting models are designed for use with the Human Motion Simulation Framework, a software system previously applied to simulating a wide range of task-oriented human behavior, including passenger car ingress and egress.

Keywords: Digital human modeling, ingress and egress, trucks

INTRODUCTION

Digital human figure models have been applied to simulation of driver ingress and egress for passenger cars, light trucks, and heavy commercial trucks (Andreoni et al. 2004; Cherednichenko et al. 2006; Dufour and Wang, 2005; Lestrelin and Trasbot, 2005; Pudio et al. 2006; Rasmussen and Christensen, 2005; Reed et al. 2008). The previous work on commercial truck ingress/egress (IE) has focused on cab-over-engine (COE) trucks, which are common in Europe and some other markets (Chameroy et al. 2008). In the U.S., the driver sits behind the engine in most heavy truck cabs (so-called conventional cabs) and the step and handhold configurations are substantially different from those of COE trucks.

Truck IE is a focus of ergonomic concern because of the relatively high likelihood of injury. Truck drivers are frequently injured due to slips and falls while entering and exiting the cab, and the design of the steps and handholds has been implicated in those injuries (Jones and Switzer-McIntyre, 2003). Lin and Cohen (1997), using data from a survey of trucking companies, reported that more than 25% of injuries, and more than 80% of the more severe injuries causing lost work days, were due to slips and falls.

As part of a larger study of truck driver IE with conventional cabs, a laboratory motion capture study was conducted. Among the goals of the study was the development of predictive methods for simulating driver IE with a wide range of step and handhold configurations. The overall simulation approach is based on the Human Motion Simulation (HUMOSIM) Framework, a hierarchical methodology for simulating complex, task-oriented human movement (Reed et al. 2006). The HUMOSIM Framework has previously been used to simulate a wide range of tasks, including passenger car IE (Reed et al. 2008). The previous IE work demonstrated the importance of flexible collision avoidance algorithms to guide the trajectories of the lower limbs when the simulated figure moves through a confined space.

The HUMOSIM Framework controls the kinematics of the limbs through a two-step process. The motion of the end-effector (hand or foot) is predicted, after which the joint angles necessary to achieve the prescribed end-effector movement are calculated using behavior-based inverse kinematics. This methodology exploits the empirical observation that end-effector trajectories are much more consistent across subjects and tasks than are joint angles, and hence are easier to model. This approach also supports generalization to alternative figure models with different joint definitions, because joint angles are not the primary control variables. End-effector translation trajectories are modeled using third-order Bézier curves, which provide a convenient and accurate parameterization of typical hand and foot motions. Previous studies have shown that hand trajectories in reaching tasks and foot translations in passenger car ingress and egress can be readily modeled using Bézier curves (Faraway et al. 2007; Reed et al. 2008). The current paper applies the Bézier parameterization to foot movements in truck ingress and develops a predictive model to assess the effects of step configuration and driver characteristics on foot movements.

METHODS

LABORATORY METHODS

A full-scale laboratory mockup (Figure 1) was constructed to simulate IE with conventional truck cabs having two steps and either interior or exterior handholds, a configuration found on more than 95% of US tractor/trailer truck cabs. A 13-camera VICON motion capture system was used to record movement data at 60 Hz. Figure 1 shows a truck driver entering the mockup wearing the passive optical markers used to track movements.

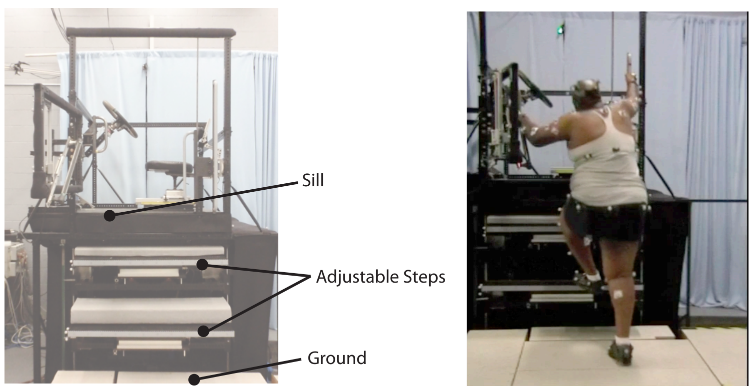

FIGURE 1. Laboratory mockup, showing adjustable steps; driver entering the mockup wearing motion-capture markers.

PARTICIPANTS

Data from 15 men and 5 women with at least two years of commercial truck driving experience (median 11 years) were analyzed for the current analysis (more than 95% of commercial truck drivers in the U.S. are men). The drivers ranged in stature from 1554 to 1862 mm and in body mass index (BMI) from 21.7 to 40.1 kg/m^2.

TEST CONDITIONS

Testing was conducted with 8 step conditions developed based on an analysis of 30 conventional truck cabs (Figure 2). The heights of the two steps and the cab floor were fixed, but the lateral positions of the two steps relative to the door sill were varied. Fifteen of the drivers were tested in all 8 conditions; five drivers were tested only in conditions one through four.

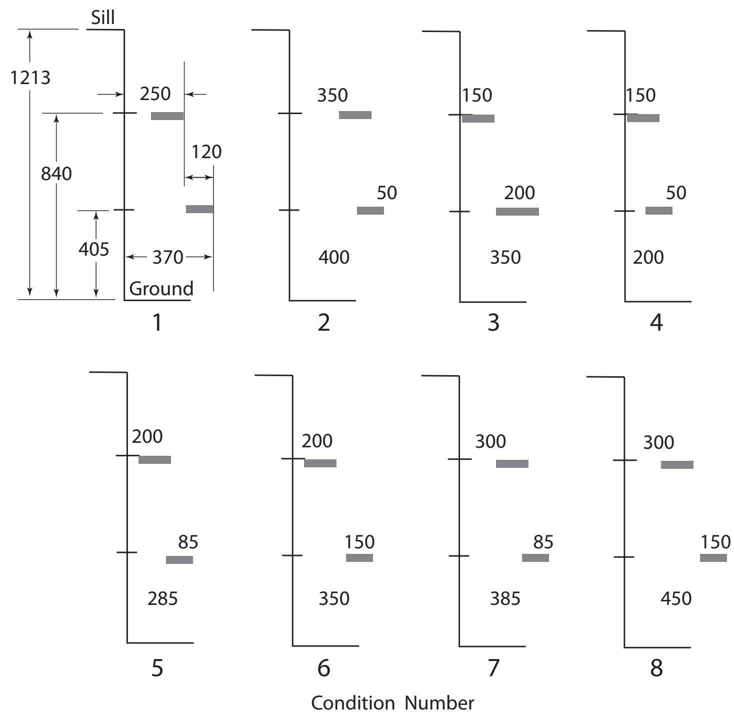

FIGURE 2. Step configurations. Dimensions in mm. Sill is at the height of the cab floor.

FOOT KINEMATICS

The analysis presented here focuses on the right and left foot moving from the ground to either the first or second step. The trajectory of each foot was modeled using the translation of single lateral ankle marker on each foot. Some participants placed their right foot on the first step from the ground, while others used the left foot. Left and right-foot trajectories were analyzed separately for analysis in each step condition.

Foot trajectories were modeled using a three-step process. The movement from the ground to the first or second step was extracted from the trial data by an automated algorithm that identified segments between stationary periods based on speed. The extracted motions, consisting of between 30 and 80 frames, were resampled using local linear interpolation to obtain 100 evenly spaced points.

Third-order Bézier curves were fit to each trajectory using a least-squares algorithm with adaptive knot assignment (Faraway et al. 2007). The third-order Bezier curve parameterizes the trajectory into two end points and two interior control points. Regression analyses were conducted to determine the effects of subject and step-location variables on the control point locations.

RESULTS

FOOT MOVEMENT PATTERNS

Out of a possible 280 foot motions (8 step conditions x 15 subjects x 2 feet + 4 step conditions x 5 subjects x 2 feet), 8 trials were excluded due to movement anomalies (e.g., slipping off of the step), leaving 272 trials for analysis. Table 1 shows the distribution of foot motions by the target step. The most common movement pattern (70% of the trials) was moving the right foot to the first step followed by moving the left foot to the second step. The left foot moved to the first step in only 30% of trials.

Table 1. Frequency of Movement with Each Foot to Each Step

Foot	Step 1	Step 2	Total
Right	105 (77%) *(70%)*	31 (23%) *(25%)*	136
Left	44 (33%) *(30%)*	92 (67%) *(75%)*	136
	149	*123*	272

BÉZIER FITTING

Figure 3 shows foot trajectories as marker data and Bézier curves for trials in step condition 1. The qualitative fit was excellent, with the Bézier curve readily capturing the basic character of the trajectories, including the departure angles from the ground and the approach angles to the cab steps. Over all trials, the 5th, 50th, and 95th percentile root mean square errors for the fits, evaluated at 100 evenly spaced points on each trajectory, were 3.8, 9.6, 37.8 mm, respectively. For comparison, the mean foot motion distance for the bottom and top steps were 689 and 1027 mm, respectively, meaning that the median root mean square error was usually less than one percent of the total movement distance.

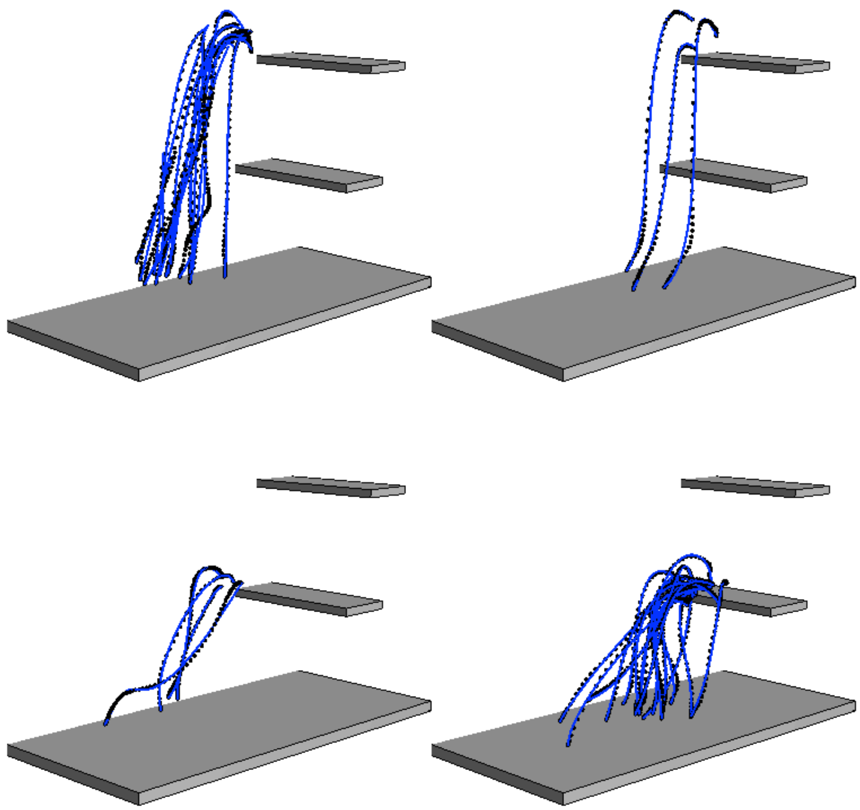

FIGURE 3. Sample trajectories fitted with third-order Bézier curves for left-foot trajectories (left) and right-foot trajectories (right). Trajectory points are shown as dots, Bézier curves as solid lines.

For digital human modeling applications, the foot placements on the ground and each step may be predicted using other statistical models (e.g., regression models), in which case a normalized trajectory analysis is more useful. Each splined trajectory was scaled to unit end-to-end horizontal and vertical displacement so that the starting point was at the origin and the endpoint was at {1,0,1}). In this representation, only the two interior control points remain to be predicted (six degrees of freedom) in the normalized coordinate system.

A multivariate statistical analysis was conducted to determine the effects of subject and test-condition factors on the shape of the normalized trajectories within each foot/step set. The interior control point coordinates were transformed using a principal component analysis and the principal component scores were predicted using linear regression. Potential predictors included driver stature, body mass index (body mass in kg divided by stature in meters squared), and three measures of the horizontal position of the two steps: step 1 relative to step 2, step 1 relative to sill, and step 2 relative to sill. Figure 4 shows the effects of varying the independent measures from 10% to 90% of the range of the independent variables in the dataset.

The analysis demonstrated that the step configuration variables did not have important effects on the trajectories after normalization. Stature and BMI affected the foot/step sets differently. Stature had a relatively large effect on the left foot trajectory when moving to the first step, with taller subjects moving the foot on a flatter trajectory. BMI had the largest effect on the movement of the right foot to the second step, with heavier drivers producing a steeper initial trajectory.

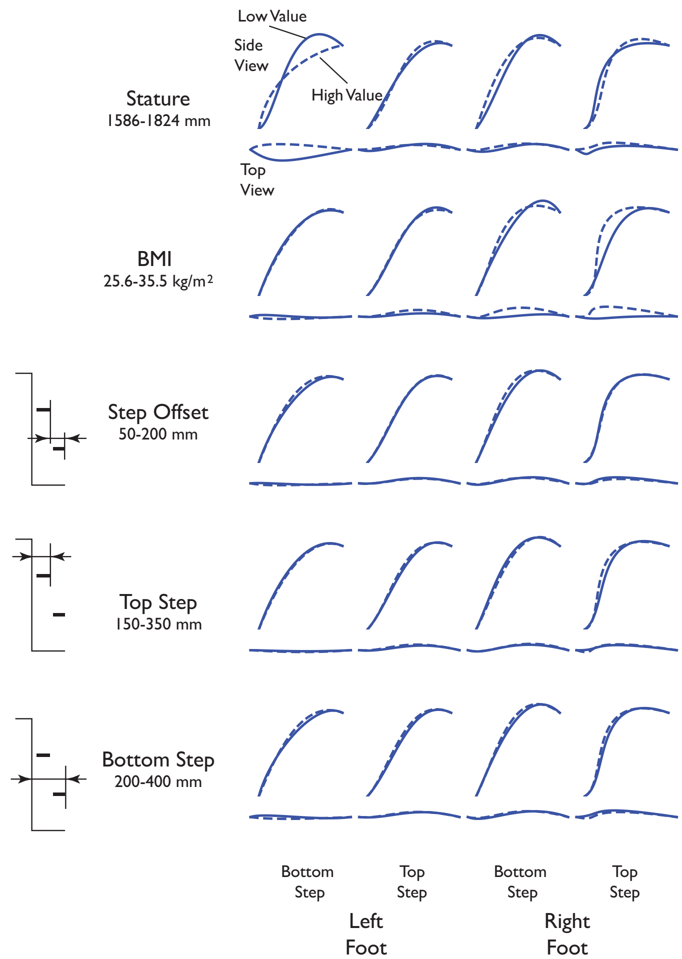

FIGURE 4. Effects of independent variables on normalized trajectories. Rows are foot/step sets. Columns are independent variables, each of which was exercised from the 10th to 90th percentiles of the values in the dataset. The normalized trajectories from all subjects and step conditions are shown in the background of each plot.

DISCUSSION

Foot motions during truck ingress demonstrate considerable regularity that is well represented by the third-order Bézier curve. A normalization approach was developed that removes both horizontal and vertical scale from the trajectories prior to statistical analysis, allowing the shape of the trajectory to be examined independent of the overall extent of the movement. The analysis demonstrated that the step configurations do not have a strong influence on the shape of the foot trajectory after accounting for scale. Relatively large anthropometric effects were seen, but only for the relatively infrequent left-foot movement to the first step and right-foot movement to the second step.

The results support a central tenet of the HUMOSIM Framework approach to human motion simulation, namely that movements of end-effectors, such as the hands and feet, exhibit smooth patterns that can be modeled with relatively simple empirical formulations. The parameters of the Bézier curve can be readily modified to impose obstacle avoidance on trajectory predictions (Reed et al. 2008) while maintaining the basic character of the motion.

The findings of the current analysis are limited by the relatively small subject pool. The trajectories show considerable residual variability that is not accounted for by overall measures of driver size. Accurate characterization of the range of driver behavior will require a larger and more diverse subject pool, particularly when multiple tactics are to be simulated. Driver behavior in the laboratory may not span the entire range of behaviors drivers exhibit in the field, and the laboratory conditions are necessarily a subset of the possible step and handhold configurations on trucks. Future work will include a more complete analysis of movement kinematics for both ingress and egress motions.

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