Changes in forklift driving performance and postures among novices resulting from training using a high-fidelity virtual reality simulator: An exploratory study

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Abstract: Virtual reality (VR) has emerged as a promising tool for training. Our study focused on training for forklift driving, to address an ongoing worker shortage, and the unknown impact of repeated VR training on task performance and kinematic adaptations. We trained 20 novice participants using a VR forklift simulator over two days, with two trials on each day, and including three different driving lessons of varying difficulties. Driving performance was assessed using task completion time, and we quantified kinematics of the head, shoulder, and lumbar spine. Repeated training reduced task completion time (up to ~29.8% of initial trial) and decreased both kinematic variability and peak range of motion, though these effects were larger for lessons requiring higher precision than simple driving maneuvers. Our results highlight the potential of VR as an effective training environment for novice drivers and suggest that monitoring kinematics could help track skill acquisition during such training.

Keywords: Forklift truck, Virtual simulator, Novice training, Motion variability

1. Introduction

Forklift trucks play a major role in warehouse and distribution center operations (Fazlollahtabar et al., 2019; Vanheusden et al., 2020). The growing warehousing and distribution sector has created a high demand for skilled forklift truck drivers, who are essential for ensuring smooth and timely operations (Lustosa et al., 2018). To be employed in warehouses and distribution centers, the US Occupational Safety and Health Administration (OSHA) regulation 1910.178(l)(6) requires all forklift drivers to be certified on their skills by an experienced trainer (Cuevas, 2010; *OSHA - Powered Industrial Trucks*). However, there is a substantial shortage of skilled forklift drivers, leading to operational challenges (Loske & Klumpp, 2021). This shortage has resulted in on-the-job training and certification of novice drivers, which is intended to accelerate the acquisition of skills and knowledge of new recruits through hands-on experiences and practical training in real-world operations.

Driving a forklift often involves navigating through narrow spaces, and skillful maneuvering around obstacles, pedestrians, and other vehicles. Forklift driving thus requires precise control, along with good hand-eye coordination and attention capabilities (Chande & Bandamwar, 2021). Developing these skills involves training and practice to achieve proficiency (Lehtonen et al., 2021). Given the complexities of forklift driving, providing novices with efficient, effective, and safe training is essential for achieving peak efficiency and productivity in warehouse operations (Choi et al., 2020; Horberry et al., 2004). Since accident and fatality rates in forklift operations are relatively high (Marsh & Fosbroke, 2015), proper training, especially for novice drivers, could reduce accident rates and, thus, injuries.

Conventional forklift training, conducted on-the-job, typically requires a sizable dedicated training area to accommodate the use of a forklift truck, or is done during actual work with coordination between trainers and trainees. This conventional approach is often limited by trainer availability, facility access, and other logistical constraints (Herrera et al., 2018); and is resource- and time-consuming and thus expensive (Vahdatikhaki et al., 2019). Training novices using a real forklift truck can also increase the risk of equipment and property damage, as well as potential for accidents due to the lack of experience (Yuen et al., 2010). To address these limitations and challenges, virtual reality (VR)-based training has emerged as a potentially cost-effective and space-saving alternative to conventional training in many industries (Abbas et al., 2023; Villiers & Blignaut, 2016). Several commercial VR systems are being used for forklift driver training (Zawadzki et al., 2019), including the Raymond VR Forklift Simulator (*Forklift Virtual Reality Simulator, Raymond*), Wolter VR Forklift Simulator (*Wolter Inc*, *USA*), Virtual Forklift VR Simulator (*Virtual Forklift*, USA), Forklift-Simulator (*Forklift-Simulator*, USA), CM Labs Forklift Simulator Training (*CM Labs*, *Canada*), and Humulo Forklift VR Training (*Humulo Engineering*, *USA*).

VR-based forklift training offers drivers the opportunity to operate virtual forklift trucks in a safe and immersive learning environment. VR training programs typically include realistic simulations of common work scenarios encountered by forklift drivers, such as navigating through tight spaces, aligning the vehicle and forks, and picking pallets/loads (Sarupuri et al., 2016). One notable advantage of VR-based forklift training is the adaptability to the specific needs of an organization, such as maneuvering in narrow warehouse aisles or safely handling heavy materials in manufacturing settings. This tailored approach helps trainees become better prepared and more confident in their skills, leading to improved performance and safety (Tarr, 2005).

Current VR-based forklift training systems provide task performance metrics to assess driver safety, such as collision frequency and penalties (Abbas et al., 2023; Yuen et al., 2010), yet these metrics may not fully reflect the multi-dimensional nature of driver skills. Similarly, using completion time as the only performance metric may not provide a comprehensive assessment of improvements in a driver's skill level (Lehtonen et al., 2021; Nolimo Solman, 2002). Beyond avoiding safety errors, skilled forklift drivers exhibit smooth and steady maneuverability (Berdiev et al., 2023; Huang & Xiao, 2019). Thus, additional performance metrics (e.g., variability in movement) could contribute to a more comprehensive assessment of training and driver skill levels (Islam et al., 2023; Wu et al., 2020). For example, Kawai et al. (2020) reported that experienced drivers often display less variability in body movement, in contrast to novices or less experienced drivers who show more erratic and unpredictable motions. Experienced swimmers (Marineau et al., 2024) and cyclists (Chapman et al., 2008) also show less kinematic variability compared to novices. However, kinematic variability among forklift drivers and its association with skill level has not been investigated in literature. If experienced and novice forklift drivers show substantial differences in their kinematic variability, it could provide new objective ways to assess performance improvement among novice drivers, beyond simple performance metrics in VR training.

The aim of this study was to evaluate task completion time and kinematic metrics extracted from several body parts as potential indicators of skill development in a VR-based forklift training with different types of driving lessons. In this study, novice drivers completed training over multiple trials and days. We expected that repeated training would increase performance, which would be reflected in decreased task completion time along with decreases in joint ranges-of-motion and movement variability. We further expected that such changes would differ with the different types of training tasks. The findings of this study would help identify specific kinematic metrics as potential skill indicators for novice forklift drivers, which in turn could help in developing more automated methods of skill tracking in the context of VR-based training.

2. Methods

2.1 Participants

A convenience sample of 20 participants completed the study (14 males, 6 females), who were recruited from the local university and community. Respective means (SD) of age and stature were 22.8 (4.3) years and 177.4 (6.4) cm for males, and 26.5 (5.8) years and 164.0 (7.6) cm for females. All participants were university students over the age of 18. They were included in the study if they possessed a valid motor vehicle driving license, self-reported having no current or recent (past 12 months) musculoskeletal disorders or pain, and had less than two years of forklift driving experience. Two participants indicated less than one month of forklift driving experience with different types of trucks (reach truck, and electric forklift), while the rest indicated no prior experience. Before collecting any data, participants provided written informed consent. The study procedures were approved by the Institutional Review Board at Virginia Tech (IRB 22-341).

2.2 Experimental Procedures

This study used a high-fidelity, VR-based order picker forklift simulator (Figure 1: The Raymond Corporation, NY, USA) which is widely used for forklift driver training across the USA and North America. An order picker is a type of forklift truck commonly used in warehouse operations, which has forks at the back of the vehicle for engaging pallets, trolleys, or roll cages for transport. The truck can also reach elevated locations, by lifting the platform along with the fork attachment. Several key components were integrated in the simulator we used: 1) a real cockpit, with physical buttons and controls; 2) a VR environment, featuring multiple order picker truck lessons; and 3) a Vive Pro Eye headset (HTC Corporation, Taiwan) attached with a Leap Motion controller (Leap Motion Inc., USA). The Leap controller tracks hand and finger movements to enable touchless interaction with virtual content (i.e., box) inside the simulator. The truck user interface is connected to the VR system, enabling participants to control the truck within the virtual environment using the physical control panel (see Figure 1a). Specifically, the steering wheel on the left side of the control interface allows rotation of the truck using the left hand, while the joystick on the right side facilitates forward, backward, upward, and downward movements with the right hand.

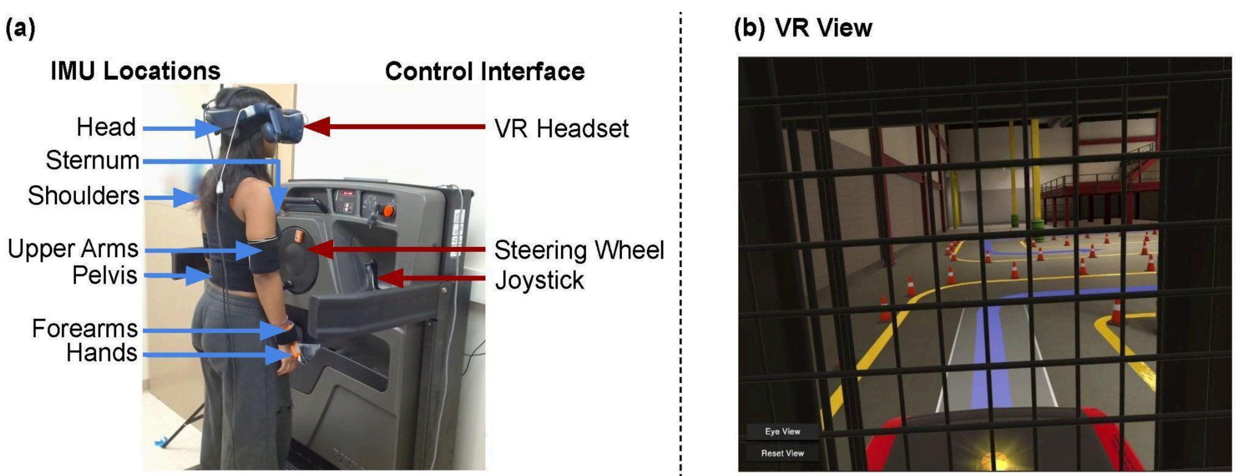

Figure 1: VR training environment showing: (a) a participant wearing inertial measurement units (IMU) on their upper body (blue arrows on the left) and the control interface of the truck simulator (red arrows on the right); and (b) a participant view of the virtual environment.

Participants completed two experimental trials on each of two separate days, with the second day scheduled within five days after the first (Figure 2). The mean (SD) separation between the first and the second days was 2.6 (1.6) days. Participants first donned the VR headset, and the VR simulator was calibrated following manufacturer guidelines, ensuring alignment of position and orientation with the physical interface. Each day included a 10-minute training activity, followed by two consecutive trials that included three different driving lessons (Figure 3). An initial training activity was included to familiarize participants with basic truck controls and the virtual environment. This training activity was similar to the main driving lessons used in the study, but participants were allowed to drive freely, rather than having to follow a specific path during the lessons. We provided the same instructional guidance during the training, but no additional guidance was provided during the trials other than prompts from the simulator.

Three driving lessons (Figure 3) were selected to represent increasing levels of difficulty: 1) L1 required driving the order picker truck without pallets or cargo; 2) L2 required engaging with a pallet, driving with the pallet attached, and extending the length of the truck; and 3) L3 required maneuvering the truck between aisles of elevated racks, and parking the vehicle close to elevated racks for picking up objects on the racks. In L1 and L2, participants received a penalty (i.e., 10 point deduction) whenever they hit the traffic cones, and they were instructed to avoid hitting cones to the extent possible. In L3, trials were terminated if participants hit the racks. Participants also had to complete a load pick up at each pick up point before progressing forward to the next point. Among the 20 participants recruited for this study, some participants could not complete L2 (1 female) and L3 (2 males, 3 females) due to the task difficulty (i.e., unable to connect the fork with the pallet or to align truck with the rack to pick up loads), and chose to voluntarily discontinue the study. Also, we terminated trials during which a participant failed the same lesson three times in a row, due to crashing the truck into the racks or damaging the pallet. So finally, twenty, nineteen, and fifteen participants completed all four trials of L1, L2, and L3, giving total trials of 80, 76, and 60, respectively. Our focus in this study was on forklift driving performance, and thus results from other non-driving tasks in the L2 and L3 are omitted (i.e., engaging pallets and picking up boxes). In L2, the driving part of the task after participants finished the pallet engagement (marked as "start" in Figure 3) was considered. In L3, participants stopped the truck and picked up boxes from five different locations. Participants had to stop the vehicle before the pick-up, and we cropped that portion of the task.

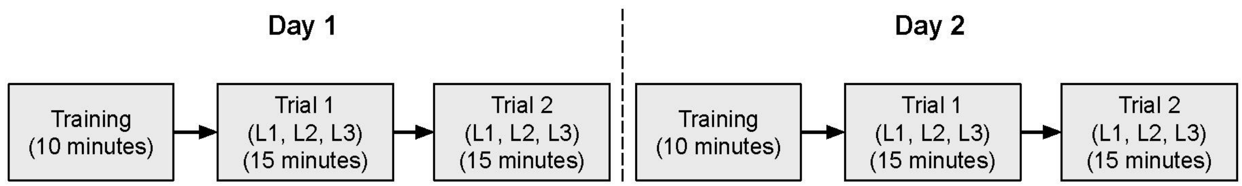

Figure 2: Overview of the experimental procedures.

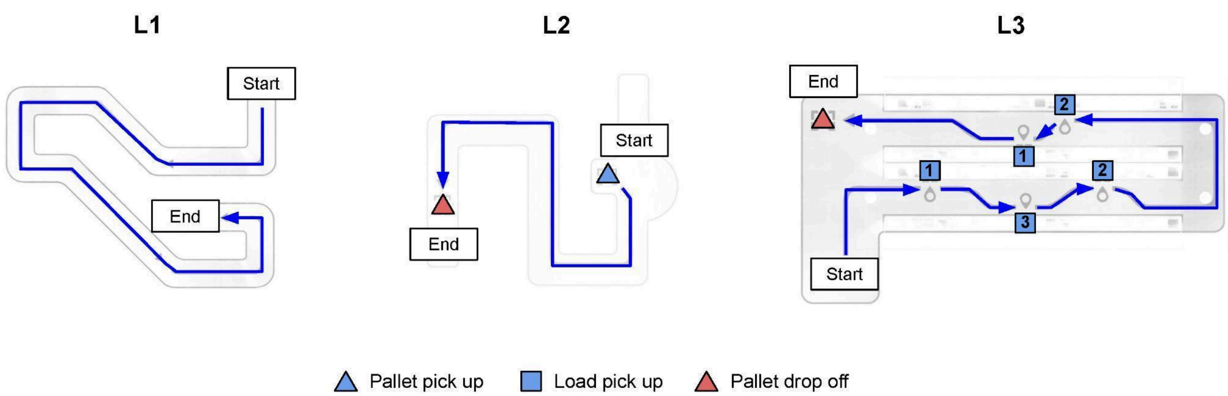

Figure 3: Maps of the three different driving lessons performed in each trial: L1 = driving without pallets with 45º and 90º turns; L2 = picking up a pallet and driving with it handling 90º-degree turns; and L3 = driving inside aisles surrounded by elevated racks while picking up loads. Numbers in L3 indicate shelf levels from which loads were picked.

Kinematic Measurements: Control of the truck involves mainly upper body movements by the driver, specifically of the head, torso, and left arm. As such, upper body kinematics were recorded (at 60 Hz) using 11 inertial measurement units (IMUs; MTw Awinda, Xsens, Netherlands). This IMU system has has been reported to provide reasonably accurate measurements of joint kinematics during dynamic activities (e.g., RMSE values ranging from 1.4–7.4^0 compared to optical motion capture system; Cottam et al., 2022; Lallès et al., 2023). Using straps and double-sided tape, sensors were attached to the head, sternum, and pelvis, and bilaterally to the shoulders (over the scapula), upper arms, forearms, and hands (Figure 3). Before data collection, the IMU system was calibrated for each participant in accordance with manufacturer instructions (*MVN Calibration*, 2023).

2.3 Data Processing and Dependent Variables

Completion time for each trial was obtained by annotating the start and end times of the driving lessons from each trial using the recorded videos and Elan software (*v6.2*; Wittenburg et al., 2006), excluding any times that involved non-driving tasks (e.g., load pick-up). IMU data were low-pass filtered (second-order, zero-lag, Butterworth filter, 5 Hz cut-off), and joint angles were derived from the filtered data based on the ZXY rotation sequence recommended by the International Society of Biomechanics (ISB; Wu et al., 2002, 2005). Specific angles were selected for analysis to understand visual focus, body positioning, and overall performance of forklift drivers: head flexion/extension and axial rotation; left shoulder internal/external rotation; and lumbar flexion/extension, lateral bending, and axial rotation. Movement variability was quantified in each lesson in a given trial using the absolute coefficient of variation (COV) for each joint angle (Bradshaw et al., 2007), and was computed as the ratio of the standard deviation to the mean. Since mean angles can have negative values (e.g., head extension), we used absolute COV to assess how movement variability differs, not whether the direction of rotation changed between experimental conditions. For each lesson in a given trial, movement magnitude was assessed by obtaining the 95th percentile range of motion (ROM), calculated by subtracting the 2.5th percentile from the 97.5th percentile values of the time-series for each joint angle.

2.4 Statistical Analyses

For completion time, repeated measures analyses of variance (ANOVAs) were performed, with *Day* and *Trial* as fixed effects. Analyses were done separately for each of the three *Driving Lessons* because differences in completion time between *Driving Lessons* do not reflect differences in skill levels due to intrinsic different duration between driving lessons. For the kinematic measurements, separate repeated measures ANOVAs were performed for each of the kinematic measurements, with *Day*, *Trial*, and *Driving Lesson* as fixed effects. To meet parametric model assumptions, all kinematic measures were log-transformed to achieve normally distributed model residuals. Summary statistics were transformed back to the original units for the purpose of presentation. Significant main effects were followed by Tukey's HSD *post hoc* pairwise comparisons, and interaction effects were explored using simple-effects testing. All statistical analyses were performed using JMP Pro (v16.0.0, SAS, NC, USA), using the restricted maximum likelihood (REML) method, and statistical significance was concluded when $p < .05$. Effect sizes are reported using partial eta squared (η^2_p).

3. Results

3.1. Completion Time

ANOVA results for completion time are summarized in Table 1; descriptive statistics and significant pairwise comparisons are provided in Appendix A (Table A.1 and A.4). For all three lessons, completion time was significantly affected by *Day* and *Trial* (Figure 4). The reduction of completion time from day 1 to day 2 was 10.3, 26.1, and 15.9% in L1, L2, and L3, respectively. Reductions of completion time from trial 1 to trial 2 in these lessons were 7.9, 22.3, and 13.9%. There was a significant interaction effect of *Day* and *Trial* only for L3. Completion time in Day 2

Trial 2 was reduced by 18.5% and 16.7% compared to Day 1 Trial 2 and Day 2 Trial 1, respectively.

Table 1: Summary of ANOVA results for the effects of *Day* and *Trial* on Completion Time [F value (p value, η^2□)]. Significant effects are in bold font.

Effect	Driving Lesson		
	L1 (N = 80)	L2 (N = 76)	L3 (N = 60)
Day (D)	**27.46 (<.001, 0.365)**	**31.37 (<.001, 0.421)**	**16.63 (.003, 0.262)**
Trial (T)	**19.84 (<.001, 0.275)**	**17.09 (<.001, 0.251)**	**7.55 (.017, 0.135)**
D × T	3.96 (.062, 0.033)	2.27 (.15, 0.014)	**8.39 (.013, 0.154)**

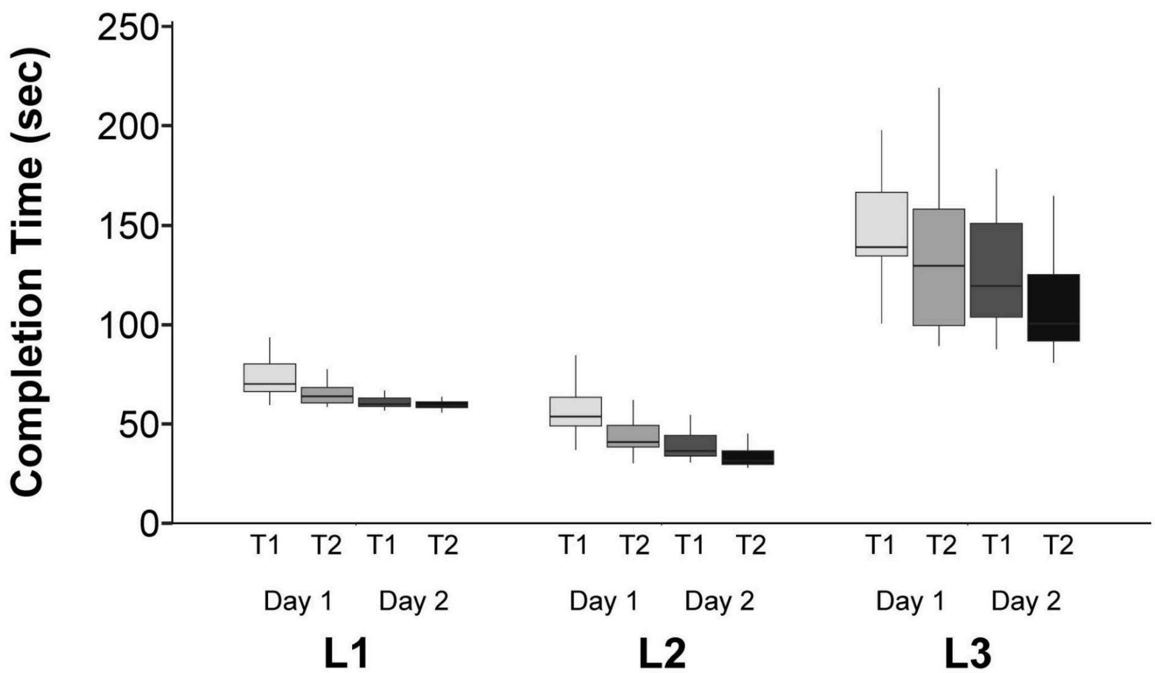

Figure 4: Boxplot for completion times across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively. The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles.

3.2. Variability and Magnitude of Segmental Kinematics

ANOVA results for the kinematic measures are summarized in Table 2; detailed descriptive statistics (Table A.2, Table A.3) and significant pairwise comparisons (Table A.4) are reported in Appendix A.

Table 2: Summary of ANOVA results [F value (p value, η^2□)] for the effects of *Day*, *Trial, and Driving Lesson* on the six segmental kinematics. Total number of trials reported is 216, across all three driving lessons. Significant effects are highlighted using bold font.

Effect	**Metric**	**Head Rotation**	**Head Flexion/Extension**	**Left Shoulder Rotation**	**Lumbar Bending**	**Lumbar Rotation**	**Lumbar Flexion/Extension**
Day (D)	COV	0.12 (.734, 0)	1.18 (.289, 0.003)	0.12 (.733, 0)	0.53 (.475, 0.001)	1.07 (.314, 0.003)	0.14 (.717, 0)
	Peak ROM	0.07 (.79, 0)	3.45 (.082, 0.033)	0.12 (.732, 0)	1.94 (.178, 0.007)	0.27 (.612, 0)	**9.08 (.008, .114)**
Trial (T)	COV	0.81 (.379, 0.002)	0.06 (.815, 0)	**10.56 (.008, 0.254)**	0.57 (.457, 0.001)	0.53 (.476, 0.001)	0.55 (.466, 0.001)
	Peak ROM	**7.24 (.015, 0.077)**	0.92 (.35, 0.002)	2.75 (.113, 0.014)	0.99 (.332, 0.002)	3.06 (.097, 0.02)	3.78 (.066, 0.024)
Driving Lesson (DL)	COV	**25.64 (<.001, 0.688)**	**11.36 (<.001, 0.273)**	**44.09 (<.001, 1.362)**	3.11 (.058, 0.03)	**12.23 (<.001, 0.266)**	**10.77 (<.001, 0.271)**
	Peak ROM	**60.21 (<.001, 1.636)**	**75.22 (<.001, 1.932)**	**33.62 (<.001, 0.975)**	**58.93 (<.001, 1.676)**	**28.74 (<.001, 0.799)**	**58.6 (<.001, 1.712)**
D × T	COV	1.12 (.304, 0.004)	0.01 (.925, 0)	0.84 (.44, 0.063)	0.24 (.627, 0)	2.21 (.154, 0.011)	0 (.949, 0)
	Peak ROM	**4.48 (.049, 0.04)**	2.14 (.162, 0.013)	**7.39 (.013, 0.072)**	3.23 (.087, 0.018)	1.84 (.191, 0.008)	0.12 (.737, 0)
D × DL	COV	0.42 (.66, 0.001)	0.19 (.828, 0)	**9.41 (.001, 0.261)**	1.81 (.181, 0.013)	0.72 (.496, 0.002)	0.24 (.787, 0)
	Peak ROM	0.33 (.718, 0)	1.22 (.311, 0.006)	0.94 (.401, 0.003)	0.13 (.875, 0)	0.03 (.967, 0)	2.74 (.08, 0.026)
T × DL	COV	**3.48 (.043, 0.038)**	0.02 (.983, 0)	0.83 (.449, 0.004)	1.24 (.302, 0.005)	0.72 (.495, 0.002)	0.83 (.444, 0.002)
	Peak ROM	**3.98 (.028, 0.047)**	0.33 (.724, 0)	**4.09 (.025, 0.044)**	0.97 (.39, 0.003)	**3.36 (.047, 0.033)**	0.77 (.47, 0.002)
D × T × DL	COV	0.73 (.49, 0.002)	0.2 (.823, 0)	3.14 (.1, 0.326)	1.34 (.275, 0.007)	0.64 (.533, 0.002)	0.15 (.859, 0)
	Peak ROM	0.3 (.746, 0)	0.49 (.619, 0.001)	2.7 (.081, 0.019)	0.64 (.532, 0.001)	0.12 (.889, 0)	2.8 (.074, 0.02)

3.2.1. Head Rotation

Variability in head rotation was significantly affected by the *Trial* × *Driving Lesson* interaction (Figure 5). In Trial 2, variability was significantly smaller in L1 than in L2 (58.7%) and L3 (75.3%). In Trial 1, variability was smaller in both L1 (58.5%) and L2 (35.8%) compared to L3. There was a significant interaction effect of *Trial* × *Driving Lesson* for peak ROM. In both Trial 1 and Trial 2, L3 had the largest peak ROM, followed by L2 and then L1. ROM in L1 decreased significantly from Trial 1 to Trial 2 (by 9.8%). A *Day* × *Trial* interaction was also observed; peak ROM in Day 2 Trial 2 was 7.5% smaller than Day 2 Trial 1.

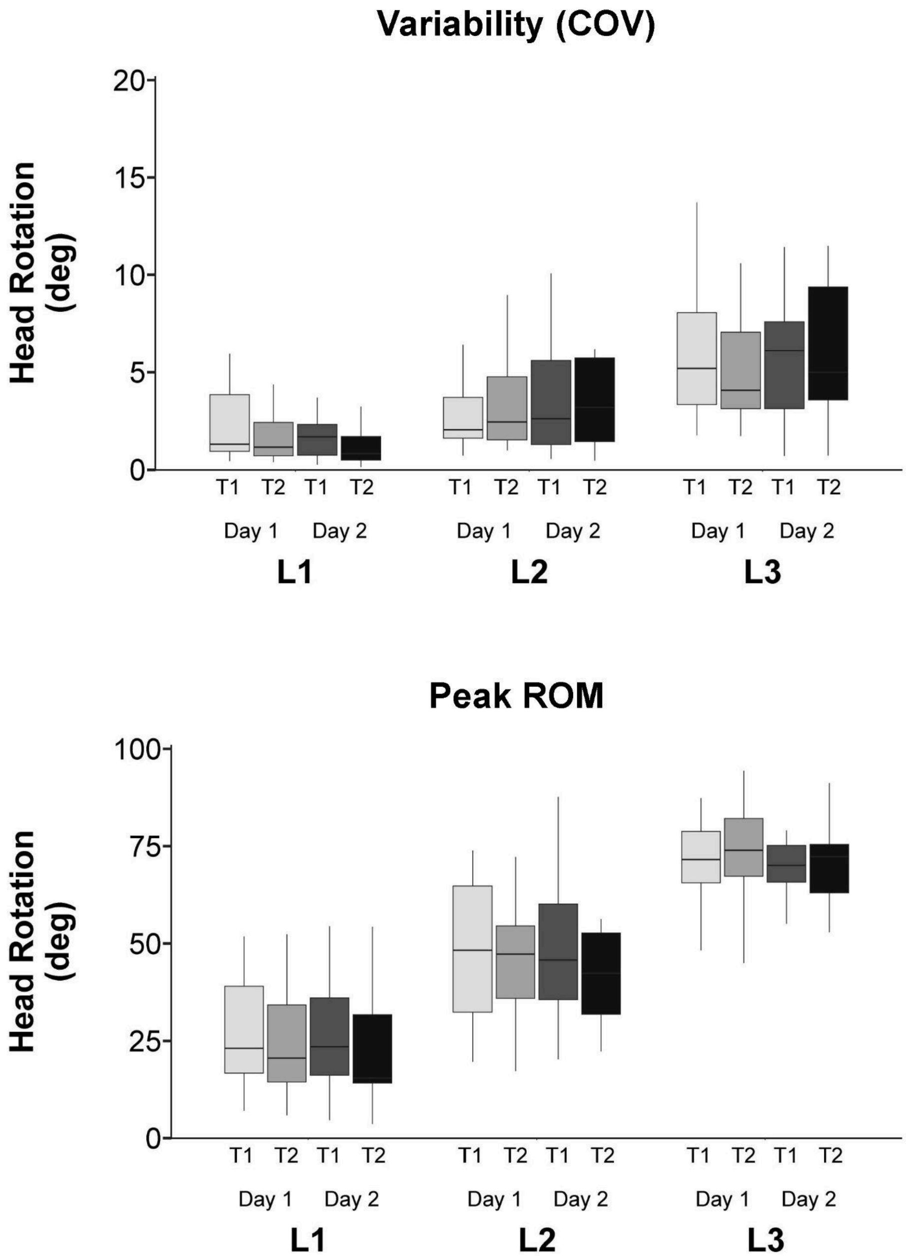

Figure 5: Boxplot for variability and peak range of motion (ROM) for **head axial rotation** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

3.2.2. Head Flexion/Extension

Variability was affected by *Driving Lesson* (Figure 6). Less variability was observed in L1 (123.9%) and L2 (96.8%) compared to L3. Peak ROM was significantly affected by *Driving Lesson*. A smaller peak ROM was found in L1 compared to L2 (30.5%) and L3 (67.9%), and in L2 compared to L3 (53.8%).

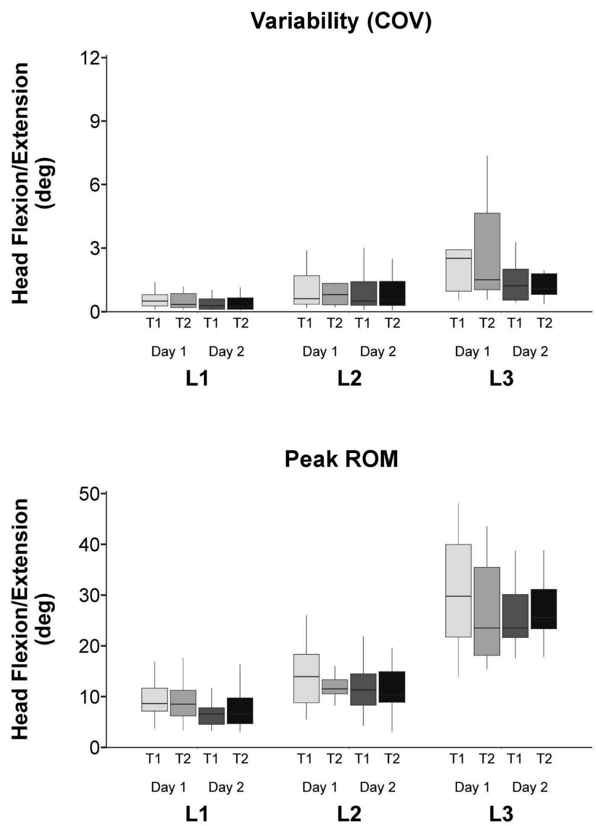

Figure 6: Boxplot for variability and peak range of motion (ROM) for **head flexion/extension** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

3.2.3. Left Shoulder Rotation

Left shoulder variability was affected by the *Day* × *Driving Lesson* interaction (Figure 7). Across both days, variability in L3 was the largest, followed by L2 and then L1. There was a main effect of *Trial*, and variability significantly decreased in Trial 2 vs. Trial 1 (42.1%). Peak ROM was affected by *Day* × *Trial* and *Trial* × *Driving Lesson* interactions. Peak ROM in Day 2 Trial 2 was 5.1% smaller than Day 2 Trial 1. In L2, peak ROM in Trial 2 was 10.1% smaller than Trial 1.

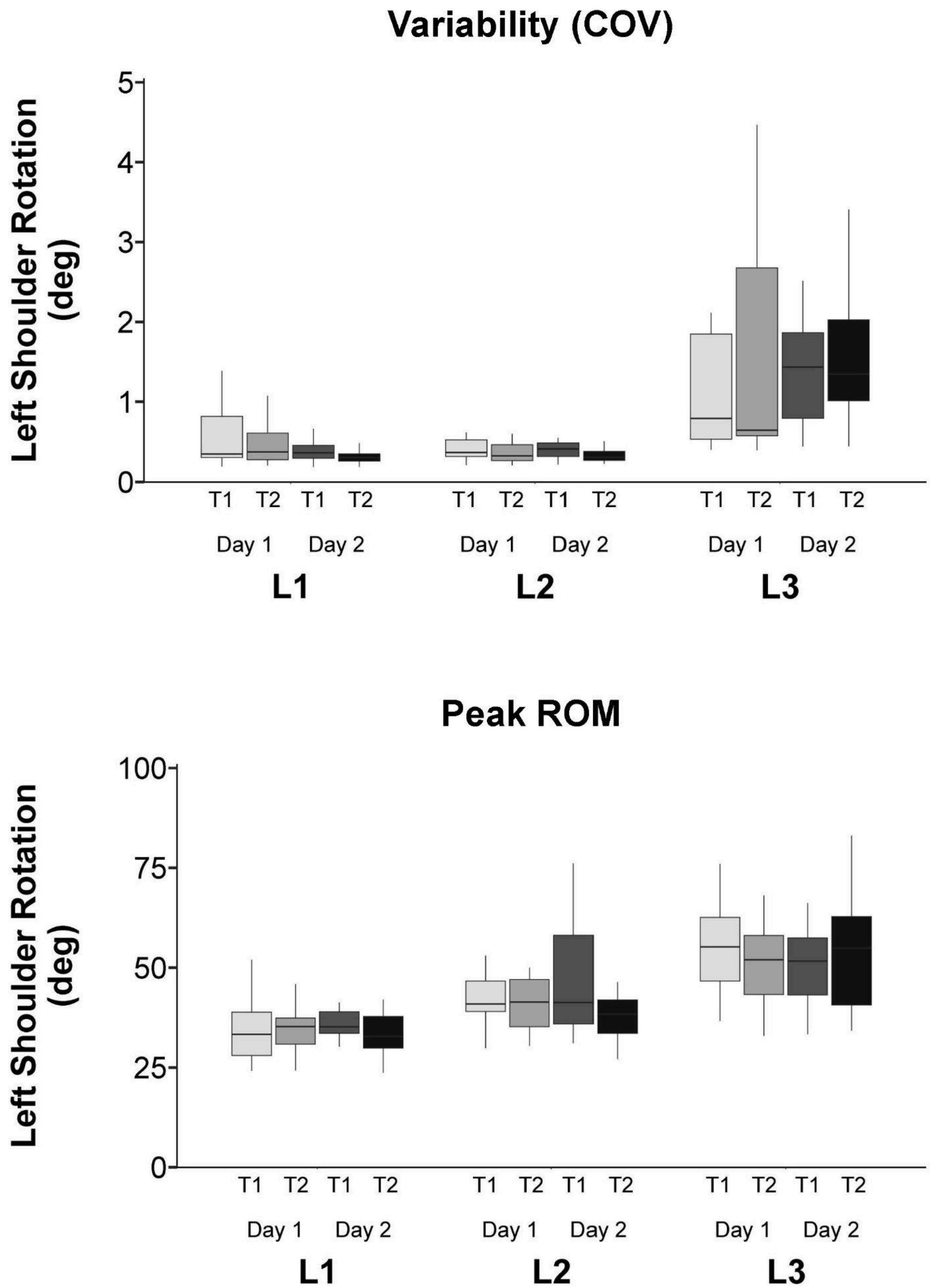

Figure 7: Boxplot for variability and peak range of motion (ROM) for **left shoulder rotation** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

3.2.4. Lumbar Lateral Bending

Peak ROM was affected by *Driving Lesson* (Figure 8); peak ROM was smaller in L1 compared to L2 (47.2%) and L3 (78.5%), and in L2 compared to L3 (59.3%). No significant effects were observed for variability.

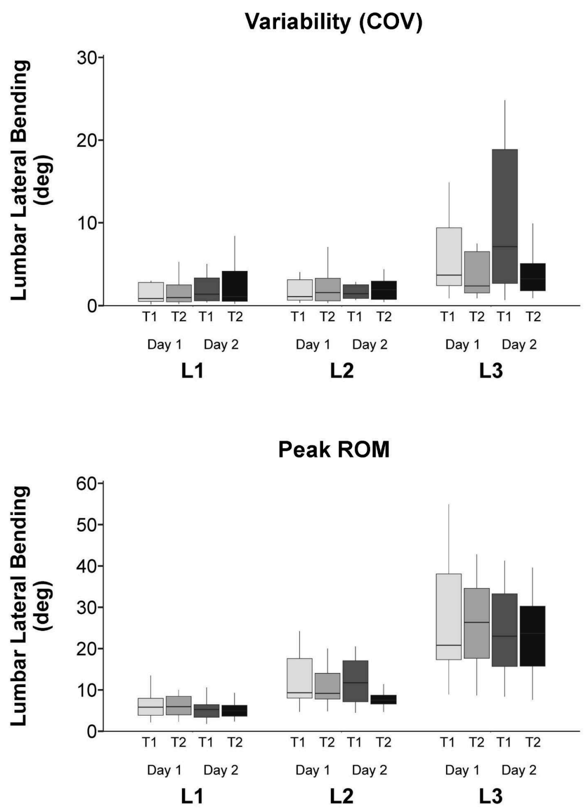

Figure 8: Boxplot for variability and peak range of motion (ROM) for **lumbar lateral bending** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

3.2.5. Lumbar Axial Rotation

A significant effect of *Driving Lesson* was found for variability in lumbar axial rotation (Figure 9). Variability in L1 and L2 were 53.5% and 72.7% smaller compared to L3, respectively. Peak ROM was affected by the *Trial* × *Driving Lesson* interaction. In Trial 1, peak ROM in L1 was the smallest compared to L2 (47.6%) and L3 (61.9%). In Trial 2, a smaller peak ROM was observed in L1 compared to both L2 (33.1%) and L3 (63.5%) and in L2 compared to L3 (45.4%). From Trial 1 to Trial 2, peak ROM decreased during L2 (24.3%).

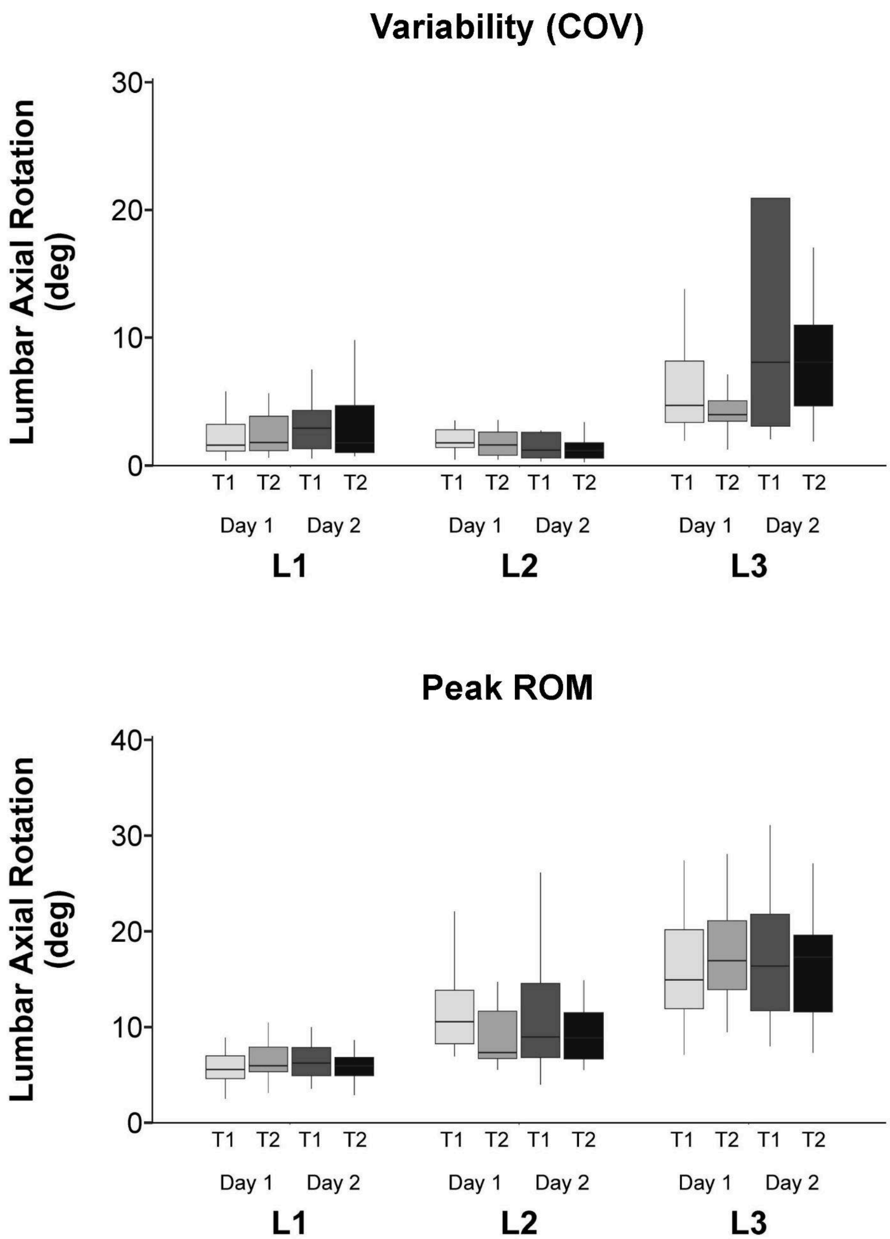

Figure 9: Boxplot for variability and peak range of motion (ROM) for **lumbar axial rotation** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

3.2.6. Lumbar Flexion/Extension

Variability was affected by *Driving Lesson* (Figure 10) and was smaller in L1 (20.4%) and L2 (83.5%) compared to L3. Peak ROM showed a significant main effect of *Day* and *Driving Lesson*. Peak ROM significantly decreased on Day 2 compared to Day 1 (23.4%). A smaller peak ROM was observed in L1 compared to both L2 (27.6%) and L3 (55.8%) and in L2 compared to L3 (38.9%).

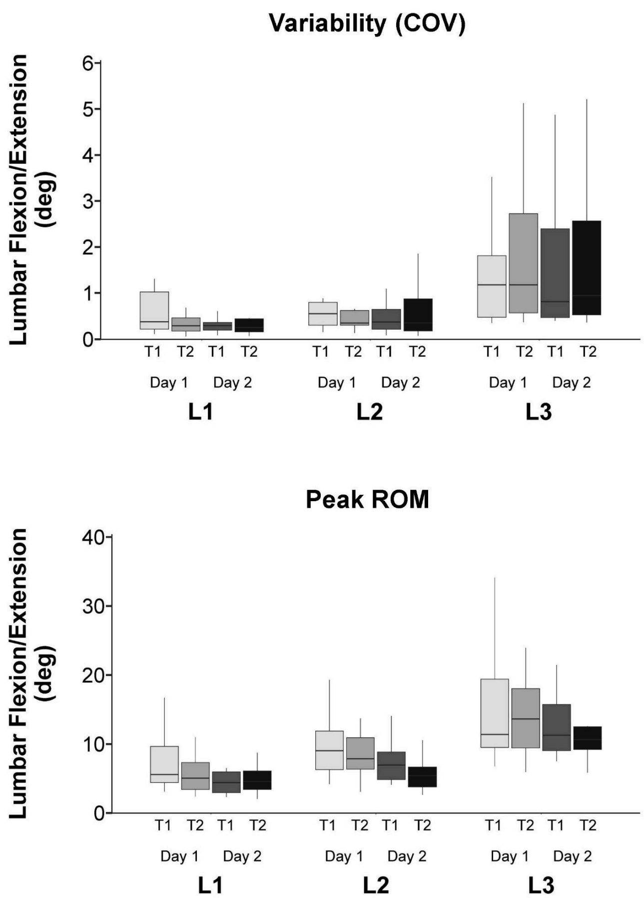

Figure 10: Boxplot for variability and peak range of motion (ROM) for **lumbar flexion/extension** across repeated trials (T1 and T2) on different days (Day 1 and Day 2) and in different lessons (L1–L3). The whiskers refer to 1.5 times the interquartile range (IQR) from the first and third quartiles. The number of trials completed in L1, L2, and L3 are 80, 76, and 60, respectively.

4. Discussion

We investigated completion time and upper body kinematics of novices operating an VR order picker truck simulator to complete three driving lessons in four repeated trials over two days. We found a decrease in task completion time with repeated training and potentially due to adaptation to the VR environment, which potentially supports our hypothesis. We also found that repeated training reduced movement variability either over multiple days or trials, specifically in head rotation, left shoulder rotation, and lumbar flexion/extension, which partially supports our hypothesis. The following discussion addresses these results in more detail, as well as the key implications of these findings in terms of measuring training effectiveness and driving skill improvement. Furthermore, we discuss potential design recommendations, based on the current findings, that could enhance future VR-based forklift training.

4.1. Performance and Productivity

Repeated VR training significantly reduced task completion time (Figure 4), implying potential benefits of such VR training, since a decrease in completion time is typically associated with improved productivity in warehouse operations (Sarupuri et al., 2016). Participants may have adapted to the VR environment with repeated training (Fransson et al., 2019), which could have reduced completion time over trials in addition to skill development. Specifically, the mean magnitude of the reductions in completion time between the first and the second days were 7.7 sec (10.3%) for L1, 13.0 sec (26.1%) for L2, and 22.3 sec (15.9%) for L3, respectively. Even with several days between training, participants exhibited a statistically significant reduction in completion time across all three driving lessons. VR simulators that provide highly immersive and realistic environments can help users retain skills (Gallerati et al., 2017; Maagaard et al., 2011). However, further work is warranted to understand the optimal VR training “dose” (e.g., number of trials and days) for novice drivers to achieve sufficient proficiency and to assess the transferability of acquired skills to real-world forklift operations. Although our current study did not extend to evaluating the transfer of training, VR simulators mimicking actual work conditions (i.e., laparoscopic surgery, motor vehicle driving) have been found to facilitate the skill transfer from virtual environments to real-life scenarios (Gallagher et al., 2013; Sportillo et al., 2019).

4.2. Segmental Kinematics

4.2.1. Variability and Magnitude for Precision Driving

The three driving lessons in this study represented distinct skill sets required of the forklift driver. Compared to the other driving lessons, consistently larger variability and peak ROM were found in L3, which demanded precise maneuvering skills. For instance, lumbar axial rotation in L1 had variability as low as 46.5% of L3 and peak ROM as low as 37.2% of L3 (Figure 9). We observed that the novice drivers often leaned toward their left or right sides to better align their vehicles with the racks before picking up an object during L3, which was not observed in the other two lessons. Of note, L3 inherently requires more varied postures and movements to meet with the specific demands of the task and, not surprisingly, leading to larger observed variability. Specifically, we found significantly greater postural variability in lumbar axial rotation, likely from participants' movements when looking around the environment and fine-tuning body orientation to achieve optimal alignment with the racks and the truck. Although some previous research has shown that less variability was observed among experienced individuals and thus suggests better skills (Kawai et al., 2020), this inference may not be true for forklift precision driving. For example, skilled performance for some types of activities (i.e., sprinting) requires larger movement variability (Bradshaw et al., 2007). During precision tasks, some amount of postural variability is needed to ensure stability as it helps correct minor errors in posture, preventing larger, more destabilizing movements (Balasubramaniam et al., 2000), which is consistent with the higher lumbar movement we observed at L3.

4.2.2. Changes in Movement Variability and Magnitude Over Repeated Trials

While we generally found larger movement variability and magnitude for precision driving over other tasks, over repeated trials we generally observed a decrease in variability with continued training for all the driving lessons. In an investigation of arm movement variability under repeated movement conditions, this variability was reduced with repeated tasks (Srinivasan et al., 2015), aligning with our observations in different forklift driving lessons. We postulate that, as participants gain more skills over repeated trials, a reduction in variability and ROM indicates better control and an attempt to gain a consistent outcome from the driving lessons performed, since larger variability is associated with reduced performance and indicates a lack of consistency (Preatoni et al., 2013). Studies investigating diverse tasks – including baseball pitching (Fleisig et al., 2009), golf swings (Langdown et al., 2012), and hand-ball throwing (Wagner et al., 2012) – all have found that variability in selected segmental kinematics decreased over time as athletes became more skilled. Wilson et al. (2008) also observed a larger variability among low-skilled athletes and a smaller variability among high-skilled athletes. So, we conclude that the decreases in variability and peak ROM observed over repeated trials among novice forklift operators indicate that these novices improve their skills through the use of a Virtual Reality (VR) simulator.

4.3. Future Forklift (Order Picker) Design and Training Considerations

As noted earlier, larger movements of the head and upper body may be necessary for precise maneuvering. However, larger movements could also cause drivers to lose focus on the truck's control and increase cognitive load, leading to slower reaction times and reduced response accuracy (Walter & Bex, 2021). To address these problems, we suggest that forklift manufacturers should consider implementing specific truck designs to enhance driver visibility while minimizing the need for excessive head and upper body rotations. One such design is to include a 360°-view system, via multiple cameras displaying the surroundings on a secondary display (Hollister et al., 2023; Kulkarni et al., 2022). Such displays (i.e., a panoramic mirror or heads-up display) has been shown beneficial in assisting forklift drivers during warehouse operations (Bulstrode, 1987; Guo et al., 2014; Matuszyk et al., 2004) and has been utilized in autonomous driving for obstacle detection (Premachandra et al., 2020). Adapting the current VR simulator to incorporate such a feature would allow for a design evaluation based on drivers' performance and behavior before implementation in real trucks.

Although our study focused on novice participants, examining the movements and other behaviors of expert drivers in similar driving situations could be valuable for developing more effective VR training. Insights from expert drivers might, for example, aid in finding the optimal level of body movements to concurrently reduce fatigue (such as in the neck region) and improve performance (i.e., smooth maneuvering). Furthermore, a performance model based on expert behavior could help establish guidelines or behavioral targets for novices.

4.4. Limitations

Our study focused solely on driving-related tasks of an order picker truck. To expand our understanding of forklift driving performance, future research should encompass more complex tasks, such as engaging the forks with pallets and loading/unloading boxes. While our findings show reduced kinematic variability with improved performance, this relationship may not hold across different types of forklift driving tasks. Such variability might also vary based on the individual's adaptive strategies. We recruited only novice participants who were all college students. The sample size used in the study was small and could limit the generalizability of our findings. Effects of biological sex were not analyzed due to the small number of female participants that volunteered. Consequently, the results obtained may not be fully representative of the general forklift driver population, whose average age is 42 years old in the US (Bureau of Labor Statistics, 2021), whereas the mean age of our sample was 23.9 years. We also did not explore the transfer of learning from VR to real-world driving environments. Evaluating how novice drivers perform in actual driving situations after VR training can provide a more detailed understanding of the effectiveness of the VR training method and its practical applicability. Also, performance in VR training can be influenced by a participant's prior experience with VR systems or games, neither of which were considered in our study but might be beneficial in future research. Finally, the limited number of trials and training days limited our ability to measure long-term effects of VR training.

5. Conclusions

We assessed the performance of novice drivers operating a VR forklift simulator over repeated trials. In addition to the commonly used completion time metric for performance evaluation in VR training, kinematic parameters were computed to help understand behavioral patterns exhibited by novice drivers. The VR training demonstrated efficacy in reducing completion time. Our findings also revealed that a smaller variability in movement was associated with improved performance, while precision maneuvering demanded a larger variability in movements. Our results highlight the potential of high-fidelity VR simulators for training novice forklift drivers. With further exploration into real-world performance and continued research, VR training could offer effective training opportunities for novice forklift drivers to improve their skills and operational safety using detailed performance assessment.

6. Declaration of Competing Interest

The authors declare that they have no competing financial interests that could have influenced the work reported in this paper.

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Appendix

Appendix A - Summary statistics for Completion time, COV, and ROM. All units for kinematics are in degrees.

Table A.1: Mean (SD) of Completion time values.

Day	Trial	Driving Lesson	Completion time (sec)
Day 1	Trial 1	L1 (N = 80)	72.7 (9.6)
		L2 (N = 76)	57.2 (12.2)
		L3 (N = 60)	156.4 (45.8)
	Trial 2	L1 (N = 80)	65.0 (5.5)
		L2 (N = 76)	42.6 (10.7)
		L3 (N = 60)	136.8 (42.2)
Day 2	Trial 1	L1 (N = 80)	63.3 (9.9)
		L2 (N = 76)	40.5 (10.2)
		L3 (N = 60)	130.7 (39.9)
	Trial 2	L1 (N = 80)	60.1 (3.7)
		L2 (N = 76)	33.3 (5.2)
		L3 (N = 60)	109.1 (24.4)

Table A.2: Mean (SD) of COV values.

Day	Trial	Driving Lesson	Head Rotation	Head Flexion/Extension	Left Shoulder Rotation	Lumbar Lateral Bending	Lumbar Axial Rotation	Lumbar Flexion/Extension
Day 1	Trial 1	L1 (N = 80)	2.9 (3)	2.4 (8.3)	1.8 (5.5)	2.7 (4)	3.6 (5.2)	7.2 (22.6)
		L2 (N = 76)	2.8 (1.8)	4.3 (9.8)	0.4 (0.2)	4.3 (6.6)	3.4 (5.1)	0.7 (0.6)
		L3 (N = 60)	5.9 (3.4)	3.3 (4.2)	1.3 (1.1)	5.8 (4.8)	6.1 (3.6)	2.9 (6.1)
	Trial 2	L1 (N = 80)	1.7 (1.2)	3.7 (12.9)	0.5 (0.4)	2 (2.4)	6.1 (14.6)	4.9 (14.3)
		L2 (N = 76)	3.4 (2.5)	96.5 (3.5)	0.4 (0.1)	3.7 (5.8)	2 (1.4)	0.6 (0.7)
		L3 (N = 60)	7.4 (10.2)	3.6 (4.1)	1.8 (1.7)	6.7 (11.5)	5.6 (4.5)	1.8 (1.5)
Day 2	Trial 1	L1 (N = 80)	2.6 (4.4)	0.5 (0.8)	0.4 (0.2)	2.5 (3)	3.3 (2.5)	1.5 (4.9)
		L2 (N = 76)	5.7 (8.6)	1 (1.1)	0.5 (0.2)	6.5 (17.4)	3.1 (5)	1 (1.5)
		L3 (N = 60)	7 (5.3)	1.4 (0.9)	1.7 (1.7)	12.4 (13.1)	20.3 (25)	11.8 (37.5)
	Trial 2	L1 (N = 80)	2.3 (5.7)	38.5 (170)	0.3 (0.1)	23.6 (88.8)	5.4 (9)	0.5 (0.6)
		L2 (N = 76)	6.2 (9.2)	1.6 (3.1)	0.3 (0.1)	2.5 (2.5)	2.3 (2.9)	0.7 (0.8)
		L3 (N = 60)	8.9 (9.3)	3 (6.2)	1.9 (1.6)	6.5 (11.8)	9.1 (6.5)	2.2 (2.7)

Table A.3: Mean (SD) of Peak ROM (95th percentile) values.

Day	Trial	Driving Lesson	Head Rotation	Head Flexion/Extension	Left Shoulder Rotation	Lumbar Lateral Bending	Lumbar Axial Rotation	Lumbar Flexion/Extension
Day 1	Trial 1	L1 (N = 80)	26.6 (13.1)	10.9 (6.7)	34.6 (7.9)	6.1 (3)	6.3 (2.7)	7.6 (4.3)
		L2 (N = 76)	47.8 (18.3)	14.2 (6.4)	43.3 (8.9)	12.3 (5.8)	12 (5)	10.2 (5.7)
		L3 (N = 60)	70.6 (11.4)	29.5 (10.7)	54.6 (11.2)	27.8 (15.2)	16.1 (5.9)	14.9 (7.8)
	Trial 2	L1 (N = 80)	24.4 (13.8)	9.9 (6.8)	34.4 (5.4)	6.1 (2.4)	6.4 (2)	6.1 (3.5)
		L2 (N = 76)	44.5 (15.4)	13.2 (6)	41.9 (8.9)	10.6 (4.2)	9.4 (4.5)	9 (4)
		L3 (N = 60)	73.1 (12.6)	26.9 (9.8)	53 (14.1)	27.6 (13)	17.3 (5.7)	13.9 (5.6)
Day 2	Trial 1	L1 (N = 80)	25.9 (13.7)	7 (3.3)	35.7 (5.1)	5.3 (2.5)	6.6 (2)	5 (3.3)
		L2 (N = 76)	48.7 (18)	11.9 (4.9)	46.2 (14.2)	11.9 (5.5)	12.5 (8.2)	7.8 (3.6)
		L3 (N = 60)	70 (10.2)	26.6 (7.7)	50 (10.1)	25.7 (14.1)	17.6 (7)	12.6 (4.3)
	Trial 2	L1 (N = 80)	23 (14.4)	7.6 (3.7)	34.2 (7.2)	5.2 (2.3)	5.9 (1.4)	4.8 (2)
		L2 (N = 76)	41.7 (11.9)	11.6 (4.5)	38.6 (6.9)	8.3 (3)	9.1 (3)	5.6 (2.2)
		L3 (N = 60)	70.1 (9.8)	27.4 (6.1)	53.7 (14.3)	24.8 (14.1)	16.6 (5.8)	12 (4.9)

Table A.4: Statistical summary of pairwise comparisons for interaction and main effects.

Variable	Main/Interaction Effect	Pair 1	Pair 2	95% CI	*p-value*	% change
Completion Time	*Day (L1)*	Day 1	Day 2	[4.85, 11.35]	<.001	10.3%
	Trial (L1)	Trial 1	Trial 2	[2.9, 8.07]	<.001	7.9%
	Day (L2)	Day 1	Day 2	[7.5, 16.58]	<.001	26.1%
	Trial (L2)	Trial 1	Trial 2	[5.1, 15.74]	<.001	22.3%
	Day (L3)	Day 1	Day 2	[10.22, 39.06]	.003	15.9%
	Trial (L3)	Trial 1	Trial 2	[3.17, 26.52]	.017	13.9%
	D × T (L3)	Day 1,Trial 2	Day 2,Trial 2	[12.68, 56.97]	0.002	18.5%
		Day 2,Trial 1	Day 2,Trial 2	[6.11, 43.95]	.009	16.7%
Head Rotation (COV)	*Driving Lesson (DL)*	L3	L1	[0.92, 1.91]	<.001	67.8%
		L2	L1	[0.29, 1.16]	.001	47.3%
		L3	L2	[0.19, 1.2]	.005	38.8%
	T × DL	Trial 2,L3	Trial 2,L1	[0.92, 2.35]	<.001	75.3%
		Trial 1,L3	Trial 1,L1	[0.48, 1.92]	<.001	58.5%
		Trial 2,L2	Trial 2,L1	[0.36, 1.65]	.001	58.7%
		Trial 1,L3	Trial 1,L2	[0.02, 1.49]	.042	35.8%
Head Rotation (ROM)	*Trial (T)*	Trial 1	Trial 2	[0.02, 0.15]	.015	15.1%
	Driving Lesson (DL)	L3	L1	[0.99, 1.58]	<.001	64.8%
		L2	L1	[0.47, 0.98]	<.001	45.3%
		L3	L2	[0.26, 0.86]	<.001	35.6%
	D × T	Day 2,Trial 1	Day 2,Trial 2	[0.02, 0.25]	.015	7.5%
	T × DL	Trial 2,L3	Trial 2,L1	[1, 1.75]	<.001	66.9%
		Trial 1,L3	Trial 1,L1	[0.81, 1.57]	<.001	62.7%
		Trial 2,L2	Trial 2,L1	[0.42, 1.07]	<.001	45.0%
		Trial 1,L2	Trial 1,L1	[0.37, 1.02]	<.001	45.7%
		Trial 2,L3	Trial 2,L2	[0.24, 1.01]	<.001	39.7%
		Trial 1,L3	Trial 1,L2	[0.11, 0.88]	.006	31.4%
		Trial 1,L1	Trial 2,L1	[0.03, 0.28]	.006	9.8%
Head Flexion/Extension (COV)	*Driving Lesson (DL)*	L3	L1	[0.66, 2.08]	<.001	123.9%
		L3	L2	[0.08, 1.52]	.028	96.8%
Head Flexion/Extension (ROM)	*Driving Lesson (DL)*	L3	L1	[0.99, 1.49]	<.001	67.9%
		L3	L2	[0.56, 1.06]	<.001	53.8%
		L2	L1	[0.22, 0.64]	<.001	30.5%
Left Shoulder Rotation (COV)	*Trial (T)*	Trial 1	Trial 2	[0.05, 0.28]	.008	42.1%
	Driving Lesson (DL)	L3	L2	[0.96, 1.7]	<.001	83.7%

		L3	L1	[0.86, 1.6]	<.001	68.3%
	D × DL	Day 2,L3	Day 2,L1	[1.12, 2.24]	<.001	88.9%
		Day 2,L3	Day 2,L2	[1, 2.15]	<.001	88.0%
		Day 1,L3	Day 1,L2	[0.52, 1.65]	<.001	75.3%
		Day 1,L3	Day 1,L1	[0.22, 1.34]	.003	24.1%
Left Shoulder Rotation (ROM)	*Driving Lesson (DL)*	L3	L1	[0.3, 0.56]	<.001	34.3%
		L3	L2	[0.08, 0.35]	.001	19.5%
		L2	L1	[0.1, 0.33]	<.001	18.3%
	D × T	Day 2,Trial 1	Day 2,Trial 2	[0.01, 0.17]	.028	5.1%
	T × DL	Trial 2,L3	Trial 2,L1	[0.29, 0.64]	<.001	35.6%
		Trial 1,L3	Trial 1,L1	[0.22, 0.58]	<.001	32.8%
		Trial 2,L3	Trial 2,L2	[0.11, 0.47]	<.001	24.6%
		Trial 1,L2	Trial 1,L1	[0.1, 0.41]	<.001	21.5%
		Trial 2,L2	Trial 2,L1	[0.02, 0.33]	.016	14.6%
		Trial 1,L2	Trial 2,L2	[0.01, 0.21]	.024	10.1%
Lumbar Lateral Bending (ROM)	*Driving Lesson (DL)*	L3	L1	[1.05, 1.67]	<.001	78.5%
		L3	L2	[0.43, 1.06]	<.001	59.3%
		L2	L1	[0.35, 0.88]	<.001	47.2%
Lumbar Axial Rotation (COV)	*Driving Lesson (DL)*	L3	L2	[0.63, 1.93]	<.001	72.7%
		L3	L1	[0.35, 1.61]	.002	53.5%
Lumbar Axial Rotation (ROM)	*Driving Lesson (DL)*	L3	L1	[0.57, 1.12]	<.001	62.7%
		L2	L1	[0.21, 0.69]	<.001	41.4%
		L3	L2	[0.11, 0.68]	.005	36.4%
	T × DL	Trial 2,L3	Trial 2,L1	[0.5, 1.27]	<.001	63.5%
		Trial 1,L3	Trial 1,L1	[0.41, 1.18]	<.001	61.9%
		Trial 1,L2	Trial 1,L1	[0.21, 0.88]	<.001	47.6%
		Trial 2,L3	Trial 2,L2	[0.14, 0.93]	.003	45.4%
		Trial 2,L2	Trial 2,L1	[0.02, 0.69]	.033	33.1%
		Trial 1,L2	Trial 2,L2	[0.02, 0.45]	.028	24.3%
Lumbar Flexion/Extension (COV)	*Driving Lesson (DL)*	L3	L1	[0.38, 1.38]	<.001	20.4%
		L3	L2	[0.33, 1.34]	.001	83.5%
Lumbar Flexion/Extension (ROM)	*Day (D)*	Day 1	Day 2	[0.06, 0.36]	.008	23.4%
	Driving Lesson (DL)	L3	L1	[0.68, 1.09]	<.001	55.8%
		L3	L2	[0.33, 0.73]	<.001	38.9%
		L2	L1	[0.19, 0.53]	<.001	27.6%

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