VR and Motion Tracking Techniques to Inform Ideal Ergonomics of Flight Attendant Service Trolley Training to Prevent Musculoskeletal Injury

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Abstract

Working as a flight attendant involves significant risks. In this study, JACK Siemens ergonomic tool was used to assess and evaluate the L4/L5 spinal forces associated with pushing and pulling a service trolley. Xsens motion tracking system was used in conjunction with Unity 3D and an Oculus Rift to create a virtual environment of an aircraft. This study revealed that several individual factors, such as body weight and height, had strong correlations with compressive spinal force, as did hip and back flexion. These findings have important implications for developing training programs aimed at reducing the risk of lower back injuries in flight attendants who perform this task on a regular basis.

Keywords
Xsens, JACK Siemens, Virtual Reality, Flight Attendant, and Injury Prevention

1. Introduction
Flight attendants have one of the highest jobs, both in terms of elevation and rate of injury. Nearly 5,000 nonfatal workplace illnesses and injuries were reported in 2019 (U.S. Bureau of Labor Statistics 2019). Also, about 13% of flight attendants are injured annually, roughly 13,500 per year. Out of that 13% that got injured, 58% were a musculoskeletal injury involving the neck, back, or shoulders, with the largest group injured being flight attendants with 4-6 years of experience. Since being a flight attendant is a very dynamic job, many different things can happen while at work, and all have associated risk factors. The most common causative factors for back injuries are, in order of prevalence, turbulence, taking luggage in and out of the overhead bins, pushing and pulling the service trolley, and opening and closing the airstair door (US Department of Labor 2023). Moreover, poor ergonomic form used across many repetitions of each task is believed to be another major factor in the rate of injury (Cobb et al. 2012; Lombardo, 2016). As a flight attendant to get the Federal Aviation Administration (FAA) certification, they need a month of training, but training time may differ for each airline. At this time, flight attendants are required to pass a medical exam that is comprised of an eye exam, blood work, ear and sinus exam, and a drug screening. However, there is no medical standard for musculoskeletal disorder prevention or a required medical exam to see if they are predisposed (US Department of Labor 2023). Help for the injury only happens after the fact, with nothing aside from the initial training as a form of injury prevention.

Currently, virtual reality has been used in many industries, varying from medicine (Mathew 2019) to practice surgeries (Desselle et al. 2020) and rehabilitation (Rutkowski et al. 2020), sports (Li et al. 2021) for ergonomic analysis and optimization (Zhao and Follmer 2018), warehouse work for injury prevention (Azizi et al. 2018), and even the judicial system for virtual court hearings (Munro and Riel 2021). With this level of success in other fields, it can reasonably be applied to flight attendant injury prevention.

Hands-on training for potentially dangerous workplace scenarios, such as dealing with complex or heavy objects, can pose risks. Flight attendants may be prone to injuries while learning to perform their tasks, and problems can also arise from prolonged use of improper form. To mitigate these risks, virtual reality could be used to provide pre-training for flight attendants, using virtual instructors who can offer feedback on form (Buttussi and Chittaro 2021). However, it is hard to visually determine if the form is bad if it only varies slightly, bringing the need for some form of machine or program to help determine it. Specifically, there hasn't been a way to determine the forces exerted on the body while completion of the work tasks.

Hence, the aim of this study is to determine the force in the spine, specifically L4 and L5, through the use of Xsens motion tracking system and JACK Siemens ergonomics tool in conjunction with Unity 3D and an Oculus Rift. It combines VR video games with motion tracking and digital human modeling to achieve this goal. In this study, a virtual environment was created using Unity 3D, in which an Oculus Rift allowed the subject to be placed inside. Once inside, the subject completed the tasks which were considered as the highest cause of injury for flight attendants. The Xsens motion tracking software was also used to record the subject's motion, which could then be analyzed in the JACK Siemens software to determine the stresses active on the body during each task. This process would be a different injury prevention method and used to analyze flight attendants' motions and forces during the most commonly injuring tasks.

2. Methods

2.1 Virtual Reality

In order to design and develop the virtual environment of the airplane, Unity 3D software was chosen as the developing software. Unity is one of the most powerful engines available for real time 3D development (Schardon 2023). It enables you to import and assemble assets, create, and import animations for use with an advanced animation system, and write code to interact with the objects. Moreover, Unity allows for parent-child relationships between items in the Hierarchy, which makes adding many objects relatively simple. Also, it has the Inspector tool, which enables rapid access to all the properties of the object so that you can make changes without constantly delving into the code (Schardon 2023). The first asset that was imported into Unity was the fuselage, which was obtained through Sketchfab, a platform that specializes in 3D modeling (Sketchfab 2020). Its position was fixed at (0, 0, 0), without rotation, but with a scale factor of 11.3 to acquire the correct dimensions. The cabin was 27.48 meters long, 3.71 meters wide, and 2.23 meters high (Modern Airliners 2022). In order to use the Oculus Rift in Unity, the Oculus integration software was loaded in the asset store. The XR plugin management in the package manager had to be updated to version 3.2.16 for Unity to connect to the Oculus. The XR interaction toolkit was additionally deployed via package management to enable additional VR features. In the project settings, the spatializer plugin was finally selected as the Oculus spatializer. For the trolley, each child's sub-portion of the cart received mesh colliders with convex checks, while the main cart received a stiff body with a mass of 15kg for safety consideration (Gee 2018; Health and Safety Executive 2023). Because the cart is only being pushed, no additional grabbing mechanisms were required.

2.2 Subjects

This study consisted of a total of 22 subjects, from which 11 were males and 11 were females. The average body height and body weight for males and females are listed in Table 1.

Table 1. Subject demographic

	Gender	Height (cm)	Weight (kg)
22 Subjects	Male (11)	179.6 ± 3.4	78.1± 5.7
	Female (11)	164.6 ± 4.2	67.2 ± 7.9

2.3 System setup

To obtain the ergonomics analysis from the body movements, Xsens software was chosen as the motion capture system. The major objective of this study is to determine how important ergonomic analysis is to assuring flight attendants can perform their duties safely, comfortably, and with the least amount of physical stress. And the only way to achieve that is to examine the biomechanics of work processes and then use the information to create better work environments. Using the Xsens MVN Awinda system (Xsens 3D Motion Tracking Technology, Enschede, Netherlands), 17 wireless sensors were fitted on the body using adjustable straps. These were distributed throughout the arms, legs, torso, back, head, feet, and pelvic area. MVN Analyze software was used to record and investigate the data that was being collected from these sensors. By creating a biomechanical model, we were able to export full kinematic data, including joint angles.

2.4 Task performance

Within this environment, the task focus was the pushing and pulling of the trolley aboard the airplane corridor, as shown in Figure 1, which is one of the most performed tasks by flight attendants while trying to distribute food and other objects to the passengers. The task consisted of having each subject be connected through sensors into the Xsens motion capture system, and into the virtual reality environment through the Oculus set and the Unity 3D setup. Once set up, the subjects were positioned inside the aisle of the airplane, on the front side of the place and with the created trolley facing them. The constraints consisted of having the subjects grab the trolley at the specific points with both their hands. After the subjects had reached this starting position, the task consisted of them pushing the trolley down the aisle, walking approximately 5 meters, and subsequently walking backwards. This was performed to imitate the real-life movement as closely as possible, because with the way the cabin is designed, flight attendants are not able to rotate the trolley in order to walk back. To gather sufficient data, each subject repeated the task for a total of four repetitions.

Figure 1. Subject performing push/pulling task.

2.5 Data analysis

After all the data was gathered, data analysis was performed utilizing JACK Siemens software. JACK is a human modeling and simulation tool for improving the ergonomics of product designs and refining industrial tasks. It enables the user to evaluate ideas for a variety of aspects, such as risk of injury, user comfort, reachability, line of sight, energy consumption, fatigue thresholds, and other significant human parameters (Siemens Software, Plano, TX, USA). With the help of this software, human sized models were created to match each of the subject's dimensions. After each of the subjects were created, they were uploaded individually into JACK and by connecting this software with Xsens to achieve the movement of both digital human models (DHMs) in sync, as shown in Figure 2. Given that the maximum push/pull force was suggested as 150N for the safety consideration (Health and Safety Executive 2023), a force was applied to each of the hands as a constraint of 75N. Its direction was pushing forwards or pulling backwards. From there, the compressive, AP and lateral shear forces were extracted as part of the data analysis. Also, the joint angles for the trunk flexion, right and left hip, right and left shoulder flexion/extension, and right and left shoulder abduction/adduction were extracted from Xsens software.

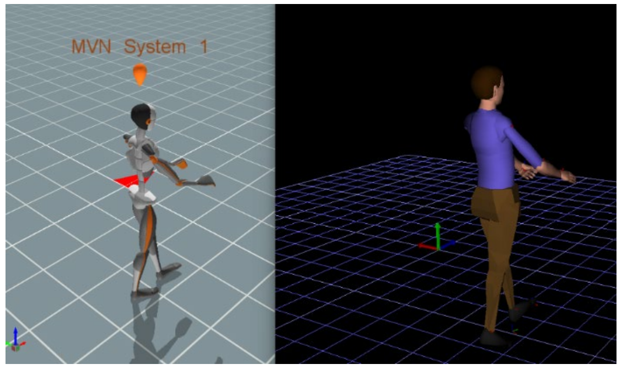

Figure 2**.** System setup with the DHM in Xsens software (left) and the DHM in JACK Siemens (Right)

2.6 Statistical analysis

For each of the variables, such as the compressive spinal force, AP shear force, and each of the join angles, a t-test was performed to evaluate the significant difference (p=0.05) between push and pull tasks, and between males and females. Additionally, we analyzed the correlation (R) between the exerted spinal forces and the anthropometric variables (body height, body weight, and trunk and hip movement) to determine which one places the aircraft attendants into a high risk of injury during their common task activity.

3. Results

3.1 Push Task

For the push task, the analyzed data were listed in Table 2, which included the compressive force, AP shear force, and the joint angles of trunk, hips, and shoulders.

Table 2. The spinal forces and joint angles were listed for the push task.
Note that the positive values mean flexion movement and the negative values mean extension movement.

S	Comp (N)	AP Shear(N)	Trunk Flex (°)	Right Hip (°)	Left Hip(°)	R_S_Fl (°)	R_S_Abd (°)	L_S_Fl (°)	L_S_Abd (°)
M1	597.1	173.4	20.7	17.4	13.4	18.3	27.6	13.9	21.5
M2	1005.2	51.7	-5.0	0.7	8.9	12.6	14.4	17.2	18.2
M3	531.3	137.4	-1.3	6.3	4.9	26.6	3.4	28.0	12.6
M4	1169.1	33.1	5.6	16.0	5.3	40.9	10.8	55.2	3.4
M5	725.2	115.2	-1.4	13.1	5.2	30.6	22.6	28.7	12.5
M6	965.5	71.9	8.9	6.3	11.1	13.3	9.4	15.0	8.9
M7	441.3	181.3	-3.8	7.8	14.1	32.1	20.5	21.6	16.8
M8	949.2	113.7	1.1	10.8	5.6	35.5	7.1	31.0	9.0
M9	854.4	86.3	7.1	9.1	5.3	36.3	29.1	13.7	20.9
M10	640.2	125.7	-8.1	14.5	1.6	20.9	4.3	12.5	13.4
M11	498.1	158.6	-2.4	14.6	8.9	49.9	29.1	32.1	18.3
F1	517.8	126.3	11.5	4.7	9.9	55.0	19.3	42.9	31.4
F2	568.8	125.7	-10.9	0.6	15.2	22.7	10.5	23.6	15.2
F3	382.8	149.2	19.3	4.3	18.6	48.9	10.0	37.7	20.3
F4	752.5	64.0	-16.0	34.5	12.4	8.8	12.3	5.9	13.6
F5	752.6	76.4	12.8	20.9	12.8	21.9	13.2	34.9	15.4
F6	298.7	148.9	4.6	6.2	7.7	27.5	25.9	28.1	22.1
F7	428.3	156.7	17.1	9.6	31.8	10.3	13.8	10.5	12.6
F8	647.6	101.5	-8.9	20.9	16.0	18.0	9.2	7.6	7.9
F9	409.5	166.3	11.6	3.4	24.2	26.7	12.9	32.2	15.5
F10	395.5	177.3	11.8	0.5	9.4	47.9	70.7	50.6	12.3
F11	369.4	175.4	1.9	8.9	12.2	44.1	12.0	48.1	8.8

*S: Subjects, M: Male, F: Female, Comp: Compressive, Flex: Flexion, R_S_Fl: Right shoulder flexion, R_S_Abd: Right shoulder abduction, L_S_Fl: Left shoulder flexion, L_S_Abd: Left shoulder abduction.

The average compressive force for males was 761.5N, while for females it was 502.1N. On the other hand, the average AP shear force for males was 113.5N while for females it was 133.4N. Only the compressive force between genders had a significant difference at $p = 0.007$. Body weight with the compressive force showed a high correlation, as r = 0.58. Body height with the compressive force also showed a high correlation, as $r = 0.66$. Trunk flexion and hip flexion were found to be highly negative correlated, as $r = -0.69$. This negative correlation showed that as the trunk flexion increased, the hip flexion decreased and vice versa. Approximately 440 N in the hand force was found to be the safety threshold, once this threshold has been reached or surpassed, the lower back will be exposed in the high risk of injury to reach the recommended safety threshold (Gallagher and Marras 2012).

3.2 Pull Task

For the pull task, the analyzed data were listed in Table 3.

Table 3. The spinal forces and joint angles were listed for the pull task.
Note that the positive values mean flexion movement and the negative values mean extension movement.

S	Comp (N)	AP Shear(N)	Trunk Flex(°)	Right Hip(°)	Left Hip(°)	R_S_Fl (°)	R_S_Abd (°)	L_S_Fl (°)	L_S_Abd (°)
M1	767.9	227.7	20.9	13.6	20.3	24.7	25.5	24.0	17.9
M2	608.8	191.0	-6.0	22.3	5.7	22.6	13.9	19.2	13.9
M3	681.9	142.3	0.0	4.5	4.6	41.1	-2.6	39.5	10.9
M4	586.0	148.7	2.0	10.7	1.8	34.8	7.5	52.3	3.0
M5	554.0	189.5	-1.8	13.2	2.4	27.7	22.4	29.6	12.9
M6	876.8	343.6	9.1	9.7	9.1	14.3	8.5	17.5	8.5
M7	470.0	132.7	-6.2	10.2	10.4	27.5	19.6	19.7	15.7
M8	600.9	163.3	0.5	13.3	3.5	37.6	6.9	30.0	7.6
M9	645.5	180.1	7.1	8.2	4.2	35.9	28.6	16.5	18.9
M10	479.4	168.1	-8.9	14.9	3.3	21.1	3.1	14.4	9.1
M11	559.5	146.1	-3.9	16.3	2.4	49.7	29.1	37.1	17.1
F1	563.8	214.9	7.9	16.1	3.5	53.9	18.9	41.4	30.8
F2	485.0	173.3	-9.3	16.4	5.4	37.1	3.1	37.3	9.3
F3	355.1	170.7	18.3	1.0	12.4	48.1	9.1	39.2	21.3
F4	420.6	171.8	-8.1	35.2	15.6	6.7	15.9	6.5	13.7
F5	394.7	178.8	10.9	16.8	6.8	21.1	13.9	33.5	14.9
F6	397.1	165.5	3.1	9.4	5.0	23.9	23.7	29.6	19.1
F7	743.4	292.5	16.2	14.5	24.1	7.6	15.3	11.5	12.6
F8	551.7	256.2	-9.4	28.4	2.2	16.9	10.2	9.0	8.3
F9	418.6	153.7	12.7	6.6	16.5	26.1	12.4	31.4	15.5
F10	590.9	181.5	11.8	5.6	3.6	45.5	21.1	50.8	11.1
F11	429.5	148.3	1.1	10.1	8.0	46.6	12.4	49.9	7.2

*S: Subjects, M: Male, F: Female, Comp: Compressive, Flex: Flexion, R_S_Fl: Right shoulder flexion, R_S_Abd: Right shoulder abduction, L_S_Fl: Left shoulder flexion, L_S_Abd: Left shoulder abduction.

The average compressive force is 621.0 N for males and 486.4 N for female, and the average AP shear is 184.8 N for males and 191.5 N for females. Between genders, the compressive force was significantly different with $p = 0.014$, as well as moderate correlation between weight and compressive force with $r = 0.56$, a moderate correlation between height and compressive force, $r = 0.59$, and a strong correlation between the trunk and hip flexion with $r = -0.76$. The estimated exerted hand force was approximately 280 N to place aircraft attendants in a high risk of injury.

In both males and females, there was a significant difference in the push and pull AP shear. The males had $p = 0.0059$, and the females had $p = 0.004$. In addition, there were significant differences in body weight and body height between the genders, with the p values of 0.049 and 4.3x10-5 for the weight and height, respectively. In both push and pull, the body weight and trunk were correlated, with an average value $r = -0.34$.

4. Discussion

This study was successful in evaluating the forces exerted on the lower back of flight attendants during their routine task of pushing and pulling food trolleys. Furthermore, the study identified the key variables that may increase the risk of injury for attendants performing this task.

The analyzed data revealed a direct and positive relationship between body weight and compressive force, as well as between body height and compressive force, which is consistent with the results in (Ji et al. 2023). It directly leads to the compressive forces observed in male subjects were higher than those in female subjects, due to the significant difference of body weight and body height between genders in this study. The study also observed a significant negative correlation between trunk and hip flexion during the routine pushing and pulling tasks, which confirms the findings of a previous study by Ji et al. (2022). Anatomically, higher hip flexion during pushing and pulling motions may minimize trunk flexion and reduce the risk of injury (Argubi-Wollesen et al. 2017). This observation provides a clear explanation for the higher compressive force applied to the back during the push task compared to the pull task. The subjects tended to exhibit greater trunk flexion when pushing, which contributed to the larger compressive force applied to the back. In contrast, during the pull task, the subjects tended to have more extension, resulting in a lower compressive force applied to the back (Kluger et al. 2014). Hence, to use the whole body when pushing and pulling would be another way to minimize the trunk flexion.

This study found a moderate and negative relationship between body weight and trunk flexion, suggesting that individuals with higher body weights tend to have lower levels of trunk flexion (Gilleard and Smith 2006). However, despite reduced trunk flexion, individuals with higher body weights may still experience high compressive forces on the lumbar spine due to the weight of their upper body. Therefore, anthropometric variables, such as body weight and height, play a critical role in minimizing the risk of injury when pushing and pulling food trolleys. Additionally, it is recommended to engage the entire body, rather than just the trunk, when performing these tasks to distribute the forces more evenly and reduce the strain on any one area of the body.

In this study, 150N force was used for both hands when measuring the compressive and A/P shear forces using JACK Siemens ergonomic software. This value was obtained from the Health and Safety Executive (2023) during a push/pull risk assessment for stopping or starting a load for safety purposes. To estimate the appropriate amount of force required to lift an object, it is generally assumed that 10N of force is needed to lift one kilogram. If we assume a friction coefficient of 1.0, then an object that is being handled should weigh around 15 kg to ensure safe pushing. However, a new article on aircraft catering trolleys revealed that a fully loaded meal trolley can weigh up to 100kg, far exceeding the established safety threshold (Harbison 2020). Handling such a heavy cart puts flight attendants at risk of injury. Therefore, it is recommended that design modifications be made to these trolleys to reduce their weight, making them more ergonomically friendly while still being able to fulfill their intended purpose.

This study utilized the Xsens motion tracking system, the JACK Siemens ergonomics tool, Unity 3D, and an Oculus Rift to assess L4/L5 spinal forces. Correlations between individual factors such as body weight and height and compressive force were identified, indicating that as these factors increase, so does the compressive force. This makes taller and/or larger individuals more susceptible to injury. Additionally, a strong negative correlation between hip and trunk flexion was discovered. These variables should be considered when training new flight attendants to make them aware of factors that contribute to the likelihood of injury.

5. Conclusion

The findings of the study will be helpful in developing interventions or training programs aimed at reducing the risk of lower back injuries in aircraft attendants who perform this task regularly. To validate the accuracy of performing tasks in a virtual environment, the same task should be ideally completed in an actual airplane. Furthermore, recruiting more volunteers who have worked or currently work in the aviation industry can aid in identifying any discrepancies between experienced and inexperienced subjects.

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Biographies

Ethan Swierski graduated with the Biomedical Engineering major and Mathematics minor at Gannon University. He has three years of research experience, including a year and a half of CAD modeling, FEA, and prototyping, as well as a year of Unity 3D and VR at Gannon University, and half a year of biomimetic robotics work at the University of Nevada, Reno. His previous papers on fabrication of and simplified models of ankle foot orthotics have been presented at RESNA in 2020, IMECE in 2020, and NEBEC in 2021.

Maria Arenas obtained the Bachelor of Science in Biomedical Engineering at Gannon University. She is fluent in both English and Spanish. She was involved in in various research projects. For example, she collaborated with a team to develop a physical model that provides live feedback on force and pressure applied during a thoracic screw manipulation. She also participated in a faculty-directed research project focused on creating a custom orthotic leg brace for a patient with cerebral palsy. She has served as a Research Assistant in the Biomedical Engineering Department, where she utilized motion tracking technology and virtual reality software to analyze human movement and prevent injuries. She also actively participated in various organizations, including the Biomedical Engineering Society, the Society of Women Engineers, and Gannon women's golf team.

Dr. Xiaoxu Ji is an Assistant Professor in the Department of Biomedical, Industrial and Systems Engineering at Gannon University. Dr. Ji's main research interests include the application of motion tracking technology in Ergonomics; the application of robotics to reduce the risk of whole-body vibration transmitted to heavy machinery operators; and the application of Artificial Intelligence (Neural Network) algorithm in modeling design.