Biomechanics and Risk Analysis
DECKED Drawer System

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Executive Summary

The objective of this biomechanical analysis study was to evaluate and quantify the effects of using the DECKED drawer system on employee biomechanics and exposure to hazardous movements and activities in a work vehicle environment. The information gathered through observations, video analyses and simulation were used to quantify risks for injuries and to determine the difference in biomechanical stresses between a work vehicle environment equipped with the DECKED drawer system and a vehicle equipped with a truck bed toolbox.

In this study, the DECKED drawer system increased safe access to truck bed storage space by 44%, reducing the risk of fall from the vehicle by 16.7%. In addition to safer access, the DECKED drawer system reduced the ergonomic risk of many common tasks performed in and around a work vehicle. Some tasks performed with the DECKED drawer system reduced back compressive forces (BCF) to below the action limit recommended by NIOSH and increased the population strength capability from 28% to 99%. The differences in BCF, required strength capabilities, joint moments, and whole body ergonomics were determined by modeling work tasks using two principle methods: 1) 3D Static Strength Prediction Program (3DSSPP™), and 2) Rapid Entire Body Assessment (REBA).

We observed a reduction in excessive reaching and trunk flexion required to access the storage space that is otherwise out of reach or difficult from the back of the tailgate and sides of the vehicle. The magnitude of these differences were often more pronounced with shorter employees (i.e. 5^{th}, 50^{th} percentile female and 5^{th} percentile male). These differences are biomechanically significant, and could dramatically reduce the risks leading to acute and chronic injuries. In addition to these benefits, the overall efficiency of many of the observed tasks increased because of improved access to storage space and elimination of hazardous movements such as jumping down from the elevated surface of the vehicle.

The work vehicle environment was characterized into 10 distinct manual material handling zones (see Figure 2) where an employee loaded and unloaded items from a vehicle. The anthropometry of the employee had a large influence on whether or not objects in the truck bed were reachable from the ground, from the side, and from the rear of the vehicle. If an object was not reachable from the ground, an employee either climbed into the bed of the truck, onto the tire or had to excessively flex the trunk forward and extend the arms to reach an object.

The DECKED drawer system was found to reduce the exposure to the frequency and severity of hazardous postures that are associated with elevated risk of work related musculoskeletal disorders (WRMSDs). The DECKED drawer system also reduced or eliminated activities such as climbing into the truck or onto the tire because an employee was able to access portions of the bed's cargo space in a safer and more ergonomic posture when the drawer is pulled out to the edge of the tailgate. The DECKED drawer system reduced the physical stress from extended reaches, shoulder elevation and abduction for a portion of the tasks that were otherwise completed using more hazardous and biomechanically challenging postures.

The major differences that were found resulted if the employee modified the tasks/movements required to access storage space, resulting in fewer hazardous movements and a reduced risk of acute injury from falls ascending/descending the vehicle. Some additional advantages noted while using the DECKED storage system were reductions in the reach distances and required shoulder elevation and arm abduction over the side of the bed when standing on the ground.

In summary, a work vehicle equipped with the DECKED drawer system showed a reduction in ergonomic risk and hazardous activities when objects were stored in the drawers or placed on the DECKED surface by:

- Increasing the amount of reachable cargo space from the ground, reducing or eliminating the need for vehicle ingress/egress and the subsequent risk of falling from an elevated surface.

- Reducing the need for an employee to jump from the vehicle, which reduces or eliminates elevated compressive loads in the lower extremities and back from impacting the ground on descent.

- Reducing the ergonomic risk associated with awkward postures and the subsequent development of WRMSDs (estimated using REBA).

- Reducing the biomechanical risk (calculated using the 3DSSPP). Back compressive force, shoulder and elbow moments and population percent capabilities were significantly reduced in 6 of the 10 measured tasks. The risk observed in some tasks were dramatically reduced from "High Hazard" to "Low Hazard" (see Table 1).

- Increasing the efficiency of tasks by reducing or eliminating extra movements and activities requiring an employee to climb into the vehicle to access storage space that is not otherwise reachable from the ground.

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Background

Manual material handling (MMH) contributes to a large percentage of musculoskeletal disorders reported annually in the United States. Musculoskeletal disorders (MSDs) often involve strains and sprains to the lower back, shoulders, and upper limbs. MSDs generate higher medical and lost productivity costs than typical occupational injuries.[1] The average incurred medical cost of back and neck sprains, strains, nonspecific pain, or neurologic spine pain is $7,989 (s.d. $3,397) and $4,219 (s.d. $1,248) for other (non-back) sprains and strains.[2] MSDs can result in debilitating pain, disability, medical treatment, and financial stress for those afflicted with them, and employers often find themselves paying the bill, either directly or through workers' compensation insurance. Employers must also cope with losing the full capacity of their injured employees. Over 25% of MSDs with a medical claim had more than 7 days of lost work time.[2] The term "ergonomic risk" is used to identify risk factors related to the work process, which affect the development of work related MSDs. Ergonomic risk refers to the physical stress factors and work place conditions, which in themselves carry the risk of damage or disease to an employee's musculoskeletal system. There is high prevalence of musculoskeletal disorders and fall injuries among employees in work vehicle environments, yet the work vehicle environment has received little attention by the research community and is an understudied workplace for ergonomic risk.

Scientific evidence shows that effective ergonomic interventions can lower the physical demands of MMH work tasks, thereby lowering the incidence and severity of the MSDs they can cause. Their potential for reducing injury related costs alone make ergonomic interventions a useful tool for improving a company's productivity, product quality, and overall business competitiveness. According to the Centers for Disease Control, National Institute for Occupational Safety and Health (NIOSH), "*very often productivity gets an additional and solid shot in the arm when managers and workers take a fresh look at how best to use energy, equipment, and exertion to get the job done in the most efficient, effective, and effortless way possible. Planning that applies these principles can result in big wins for all concerned*." [3]

MMH may expose employees to physical conditions (e.g., high force, awkward postures, and repetitive motions) that can lead to injuries and lost productivity. Improving the fit between the demands of work tasks and the capabilities of the employees is essential to avoid increased ergonomic risk and subsequent injuries. For less structured work environments, which are common in industries where a vehicle serves as the main component of the working environment, minimizing the mismatch that occurs when accessing objects stored and transported within the vehicle can reduce risk. In short, changing your workplace by improving the fit between the job demands and employee capabilities can benefit your workplace by reducing the number of potentially injurious events from occurring. The DECKED drawer system enables this reduction because the work vehicle environment is improved to provide access to otherwise inaccessible locations in the vehicle, without requiring overextension, overreaching and climbing into and out of the vehicle.

According to the 2019 Workplace Safety Index, published by the Liberty Mutual Insurance Group [4], overexertion and falls account for 23.65% and 25.71% of all costs of disabling injuries, respectively. Injuries and illnesses from employees using work vehicle environments such as the one studied for this project are not specifically reported by the Bureau of Labor Statistics. However, jobs in the service, trade, transportation and utilities, and construction industries commonly utilize work vehicles, are mobile, and comprise variable tasks. These industries also account for a majority of workplace injuries requiring days away from work across all industries. Overexertion and bodily reaction is the leading nonfatal injury event involving days away from work, representing 34% of all such injuries.

Improper exit from a vehicle exposes an employee to two major potential injury mechanisms. First, the musculoskeletal system is subjected to elevated and potentially injurious levels of impact force during the descent to the ground. Second, the employee may slip and fall immediately after landing, possibly leading to various bodily injuries (e.g. fractures), even fatalities. In a study by Fathallah and Cotnam[5] musculoskeletal loading increased by as much as 7 – 10 times body weight when jumping from a commercial truck tailgate. These forces

could also easily exceed the allowable stress of spinal loading recommended by NIOSH and are largely a function of posture and technique when descending from an elevated surface.

Non-impact injury or illness resulting from excessive physical effort can be avoided by improving the work environment. Common work activities include: lifting, pulling, pushing, holding, carrying and throwing. Injuries or illnesses resulting from a single or prolonged instance of free bodily motion occur during common work activities including: bending, crawling, reaching, twisting, climbing, kneeling and walking or running without other incident (such as falls to a lower level or on the same level).

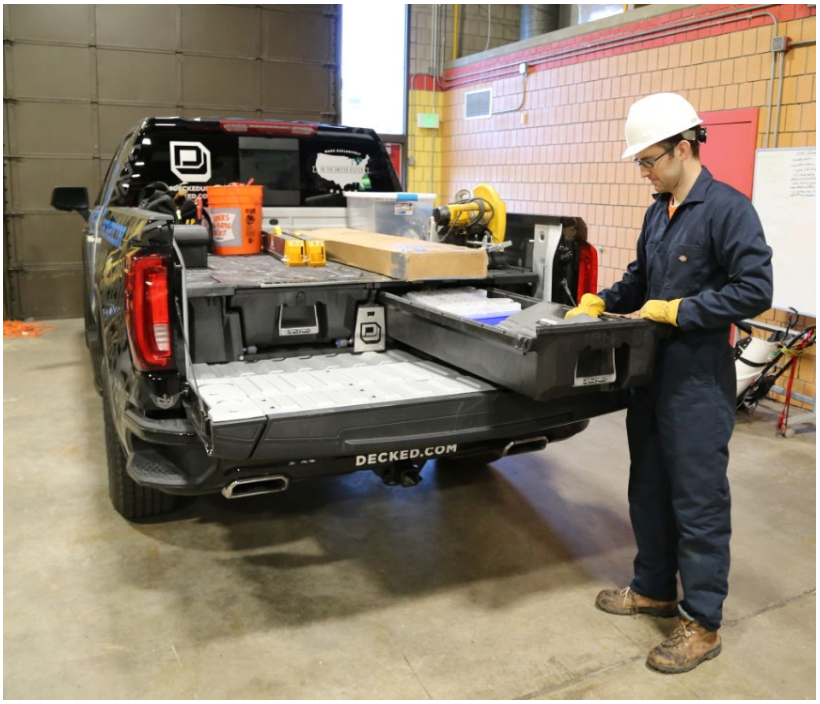


Figure 1 - Typical Work Vehicle Environment with a truck, DECKED drawer system and a toolbox.

Work Vehicle Environment

Falls from vehicles and equipment represent a large number of injuries resulting in lost time and can even be fatal. Injuries and illnesses specific to work vehicle environment are not clearly defined by the Bureau of Labor Statistics or in any other published research that was available at the time of this report, however, the nature of work tasks and activities performed by employees engaged in industries using work vehicle environments ranks near the top of all industries for work related injuries with lost days.

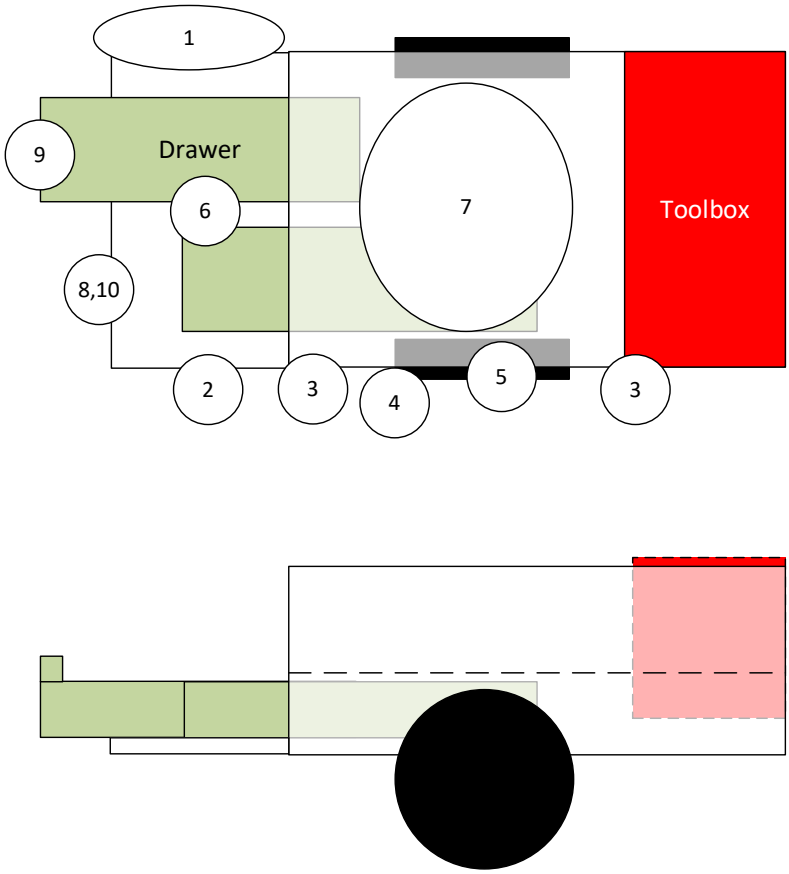
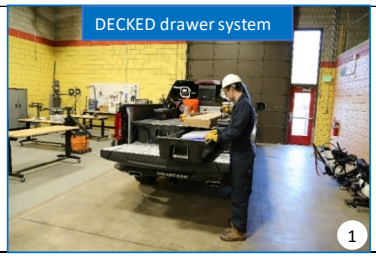
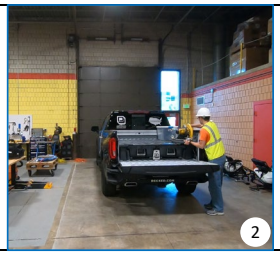
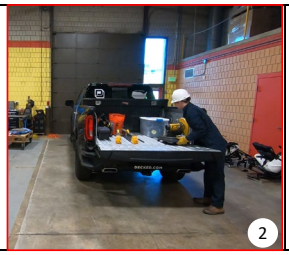
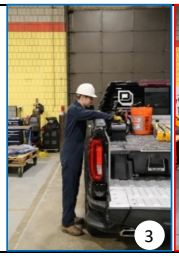
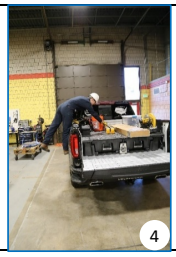
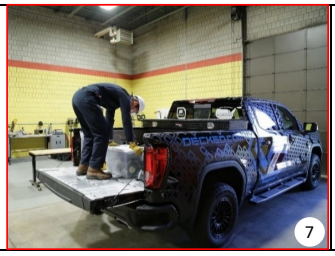
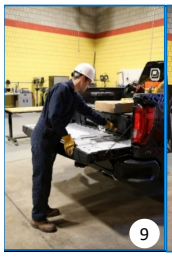
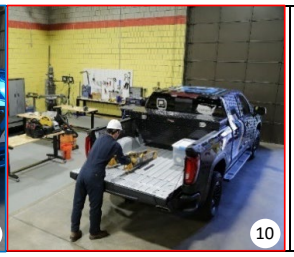


Figure 2 - Task by location around vehicle. The numbers in each bubble correspond to the task descriptions found in Table 1.

For the purpose of this report, we define the work vehicle environment as a truck bed and storage/drawer systems located in the bed (see Figure 1). The main tasks investigated are described in Table 1. We studied the effect of using the DECKED drawer system on the ergonomics, safety and biomechanics of a user handling objects by loading or unloading objects from the vehicle. A schematic of the tasks by location around the vehicle can be seen in Figure 2. For tasks in Zone 7, the lifting posture and resulting biomechanics were essentially unchanged between the two environments. For these tasks, models were only run for one environment. Zone 3 is duplicated on each side of the tire and was modeled once. Zones 2-5 are also mirrored on either side of the truck bed. For the truck toolbox located at the front of the bed, only a limited number of additional tasks were performed that were not observed while accessing the bed from the side or while standing in the bed.

Table 1 – Representative Tasks and Identified Hazards for a Work Vehicle Environment (listed by task number)

Representative Task Image	Task Name	Task Description	Hazards	Ergonomic Risk Reduction
 	Lift at Tailgate	Worker lifts objects from drawer or tailgate. If objects are not stored in a drawer and are located within reach from the truck bed, the worker can manually handle the object without ingress into the truck bed.	-Lifting objects with a vertical height above 30" -extended reach -trunk flexion -Back and shoulder stress	Low DECKED drawer system reduces stress by facilitating more erect posture and reduced trunk flexion and over reaching
 	Reach and Lift at Tailgate Corner	Worker stands at the corner of the tailgate to reach objects. This can occur for objects in drawers or on the DECKED or truck bed surface.	-Lifting objects with a vertical height above 30" -extended reach -trunk flexion -trunk rotation -Back and shoulder stress	Low/Moderate DECKED drawer system modifies risk by reducing trunk axial rotation and flexion
  	Reach and Lift from Side of Vehicle	Worker reaches over side of bed to grasp and lift objects located on the DECKED and bed surface or in the Tuckbox located near the cab.	-High shoulder stress -Shoulder elevation and arm abduction -Contact stress to the thoracic outlet while lifting	Moderate/High† DECKED elevates objects 12" from truck bed allowing greater percentage of population to reach from ground
 	Reach and Lift from Tire	Worker stands on truck tire to access objects located outside reach capability. Behavior is more common with Truckbox and objects located away from sides.	-Imbalance, unsteady -High risk of slip and fall -Trunk flexion and arm extension	High/Low† DECKED reduced/eliminated exposure when objects can be placed in drawers and accessed from tailgate. Only minor reduction with objects located on DECKED surface.
 	Lift in Truck Bed	Worker lifts objects located on DECKED surface or from bed. Similar posture observed anywhere in bed for objects not reachable standing near edge by tailgate.	-Fall from height -Impacts to legs and back from jumping down -Low back stress from lifting	Moderate† DECKED surface elevates objects 12" from surface, reducing trunk flexion and back compressive forces while lifting.
  	Pull at Tailgate	Worker reaches into the vehicle to pull objects from bed or DECKED surface to tailgate. Worker pulls drawer from DECKED system to access objects.	-Shoulder stress from pulling -Trunk flexion reaching into bed	High DECKED drawer system reduces pull forces and makes objects accessible without reaching.

† The DECKED drawer system reduces the frequency of occurrence for these tasks and changes task requirements to resemble Task 2: Lift at Tailgate. When objects are placed on the DECKED surface rather than in a drawer, there is little change in risk when using the DECKED drawer system.

Methods

A work vehicle environment was setup to study the tasks described in Table 1. These tasks were performed for the following conditions: DECKED drawer system Load and Unload, and Toolbox/Truck Bed Load and Unload. A variety of tools and equipment was selected to load and unload from the truck to simulate how an employee might load and unload the storage systems at a worksite.

Additional whole body ergonomic risk was defined by modeling the work tasks using the Rapid Entire Body Assessment method.[6] REBA divides the body into sections to be coded independently, according to three movement planes and offers a scoring system for muscle activity throughout the entire body, where manual handling may happen.

A coupling score is assigned to indicate how loads are handled in the hands. REBA also gives an action level with a sign of importance to direct attention to tasks with high exposure to risk factors associated primarily with awkward postures. A summary of Action Level by REBA score is found in Table 2. Body kinematics were simulated for 5th, 50th and 95th percentile female and male when the object location was reachable. Some of the lifting tasks such as reaching over the side of the bed to access objects were not possible for smaller employees without changing the task parameters (i.e. ingress into the bed, or climbing onto a tire).

Table 2 – REBA action levels and risk levels by REBA score

Action level	REBA score	Risk level	Action (including further assessment)
0	1	Negligible	None necessary
1	2–3	Low	May be necessary
2	4–7	Medium	Necessary
3	8–10	High	Necessary soon
(4)	11–15	Very high	Necessary NOW

Consistent hand positions were used in the analyses derived from how the subject actually performed each task. The horizontal distance (H) was measured in the sagittal plane from the midpoint of the subject's ankles to the center of his hands. Vertical values were measured from the surface to the center of the hands for each task. The load/trunk asymmetry values relative to the mid-sagittal vertical plane (0–30°) reflect the range that was observed during the video analyses.

A back compressive force (BCF) of 770 lbs is comparable to the NIOSH Lifting Index (LI) of 1.0, which represents the point at which 99% of males and 75% of females are supposedly protected from developing lifting-related back pain[7, 8]. A BCF of 1430 lbs is comparable to a lifting index (LI) of 3.0 where only 25% of males and 1% of females are said to be protected. To exploit the differences in risk associated with each work vehicle environment, simulations for each task and each anthropometry (5th, 50th, 95th percentile male and female) were created for 5 different load conditions (5, 10, 20, 35, 50 lbs). A total of 392 models were created using the 3DSSPP.

Results

A Task/Hazard analyses was conducted for each of the tasks that was observed and simulated. A summary of these observations is found in Table 1. An indication of the magnitude of risk reduction observed while using the DECKED drawer system is labeled High, Medium, and Low.

The greatest differences in risk between the two work vehicle environments was largely due to eliminated hazardous tasks such as pulling objects from the bed or climbing into the bed or onto a tire to manually handle objects unreachable from the ground without the DECKED drawer system. Figure 3 and Figure 4 identify the risk scores for each of the analyzed tasks using the REBA. As seen in these figures, the ergonomic risk of tasks performed using the DECKED drawer system were always as low or lower than the Toolbox and no storage system work vehicle environments.

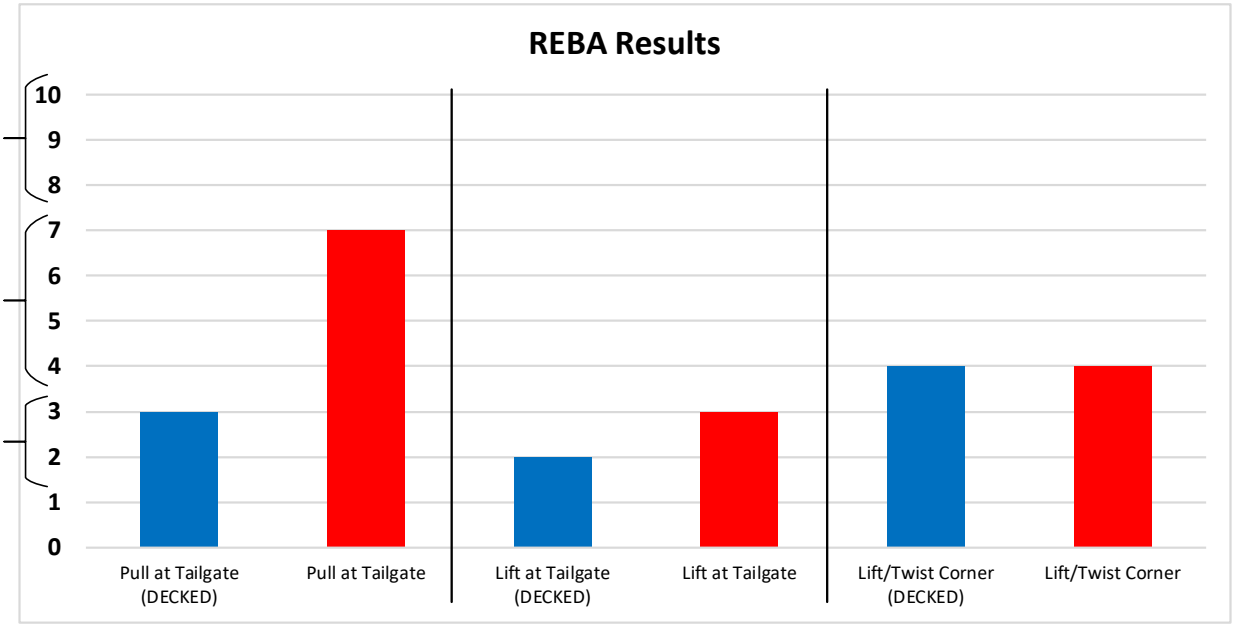


Figure 3 - REBA Results for tasks 8-10, 1, and 2

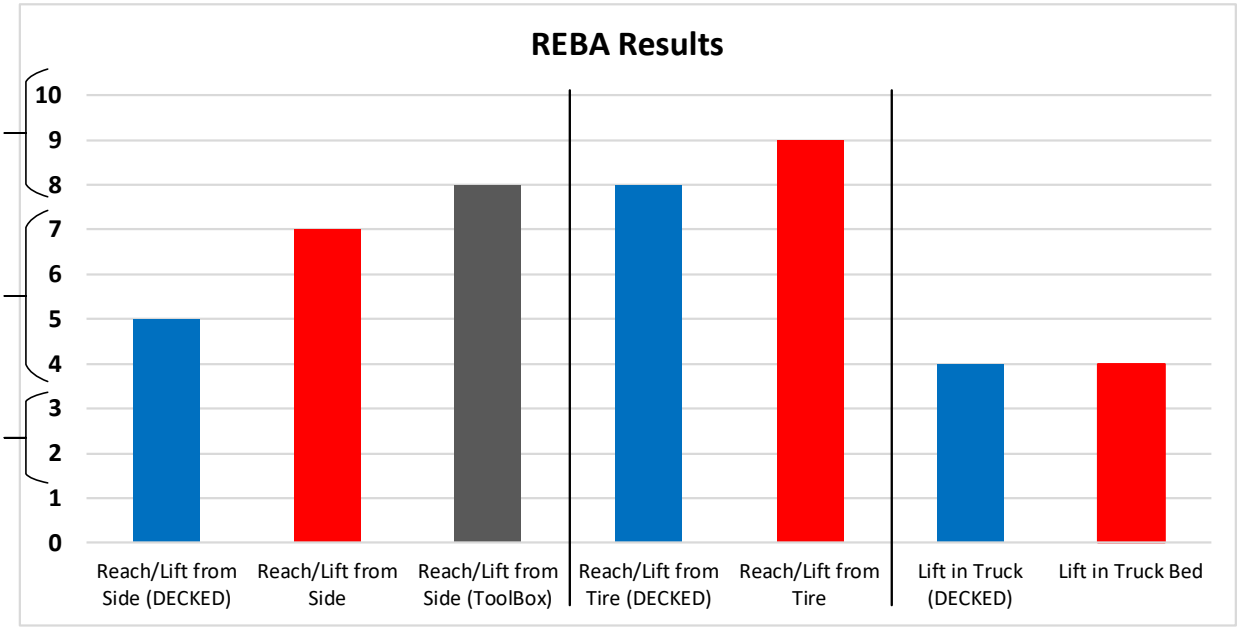


Figure 4 - REBA Results for lifting tasks 3, 4 and 7

The most significant differences between work vehicle environments resulted when objects were able to fit into the DECKED drawer system and could be translated from locations in the bed that were not accessible while standing on the ground and either reaching over the truck bed from the sides, or reaching from the rear of the truck bed near the tailgate. In Figure 8, the highlighted area with light red hatch marks illustrates where contents in the bed would be unreachable without first jumping and reaching from the side of the bed, climbing into the bed or standing on a tire. This volume represents nearly 42% of the total cargo volume of the truck box (standard bed - 6'6" long).

Analyzed Tasks

The following sections provide a summary of the results for each material handling zone and task that was analyzed. Please refer to Figure 2 for spatial reference of each zone and a brief task description.

Task 1: Lift at Tailgate

Minor reductions in risk for MSD were observed if an employee maintained an upright posture rather than flexing the trunk and reaching across the tailgate to grasp and manually handle objects. When objects were accessible at the tailgate using the DECKED drawer system, the tasks were similar for both vehicle environments. If an object was heavy (greater than 15 lbs) the employee would increase exertion to lift the object out of the drawer, rather than slide and hold the object closer to the body without the drawer. This represented a minor increase in BCF, shoulder and elbow moment for the DECKED drawer system.

Task 2: Reach and Lift at Tailgate Corner

Minor reductions in risk were observed when using the DECKED drawer system by reducing the degree of trunk rotation while reaching and twisting to access objects near the back corner of the truck. For objects stored in the back of the drawer, the postures between work vehicle environments were similar.

Table 3 - % difference in L5/S1 Back Compression, Shoulder and Elbow Moments for Task 3

Population %tile	L5/S1 (lbs)	Shoulder (in-lbs)	Elbow (in-lbs)
F5	-	-	-
F50	-	-	-
F95	-3.1	-8.0	-45.2
M5	-	-	-
M50	0.2	0.3	-20.3
M95	8.0	18.4	-32.1

F = Female, M=Male, - indicates the object was unreachable

Task 3: Reach and Lift from the Side of Vehicle

A moderate reduction in risk was observed because the DECKED drawer system elevates the storage surface by 12" from the bed. Raising the object's vertical location did little to change biomechanical stressors from lifting from the ground, but enabled access to the population that was otherwise unable to access the objects from the ground (Figure 5). Because the objects were not reachable without the DECKED drawer system for the Female 5th, 50th and male 5th percentiles, no difference was calculated. Employees in these percentiles would have to climb into the vehicle, jump and reach, or climb onto a tire to reach these objects without the DECKED drawer system.

Task 4-5: Reach and Lift from Tire

This task represents a high hazard due to the imbalanced nature of the task, poor standing surface, and reaching required to grasp objects located outside the reachable zone from the ground. A minor reduction in required trunk flexion was observed using the DECKED drawer system, but the primary risk in this task was for falls. This risk was similar between both work environments.

Task 6-7: Lift in Truck Bed

When objects are reachable on the DECKED drawer system's surface while standing on the tailgate or edge of the truck bed, the BCF, shoulder and elbow moments decreased by 10-33%. This is because the vertical height of the object increased by 12". The majority of the cargo space in the unreachable zone would require the employee to step onto the DECKED drawer system, which has the same lifting biomechanics as lifting in the bed of the vehicle.

Task 8-10: Pull at Tailgate

The DECKED drawer system is equipped with rollers which reduces the sustained pull force to about 5 lbs when level for a drawer containing 70 lbs of objects. Compared to the force and

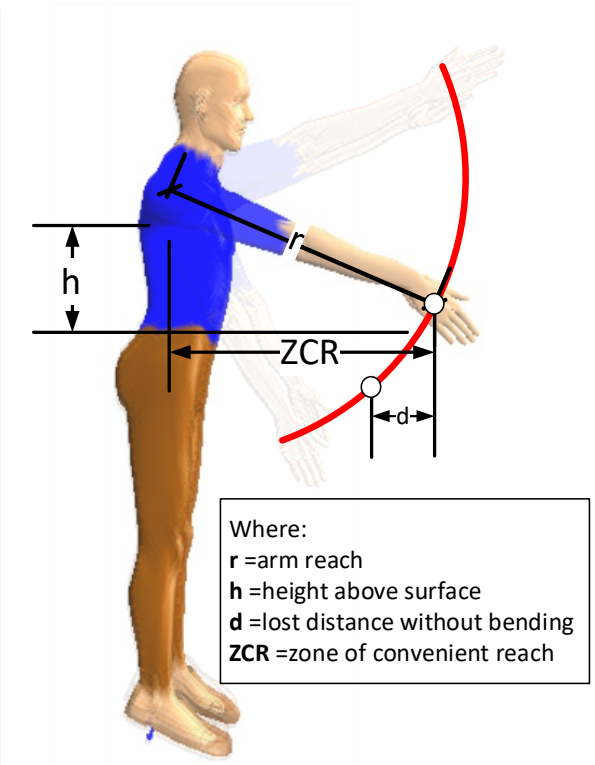


Figure 5 - Zone of Convenient Reach. Reach distance improves with DECKED drawer system.

moment required to pull an object from the truck bed to the tailgate, the average reduction in low back and shoulder stresses using the DECKED drawer system was significant (see Figure 6). The low back stresses were reduced by nearly 50%. The BCF values for the DECKED drawer system are considered "safe" according to NIOSH, whereas the values without the DECKED drawer system exceeded the recommended action limit of 770 lbs for males (827 lbs). The percentage of the population capable of safely exerting the required pull forces went from 99-100% using the DECKED drawer system to 28-45% without the DECKED drawer system for females and males respectively.

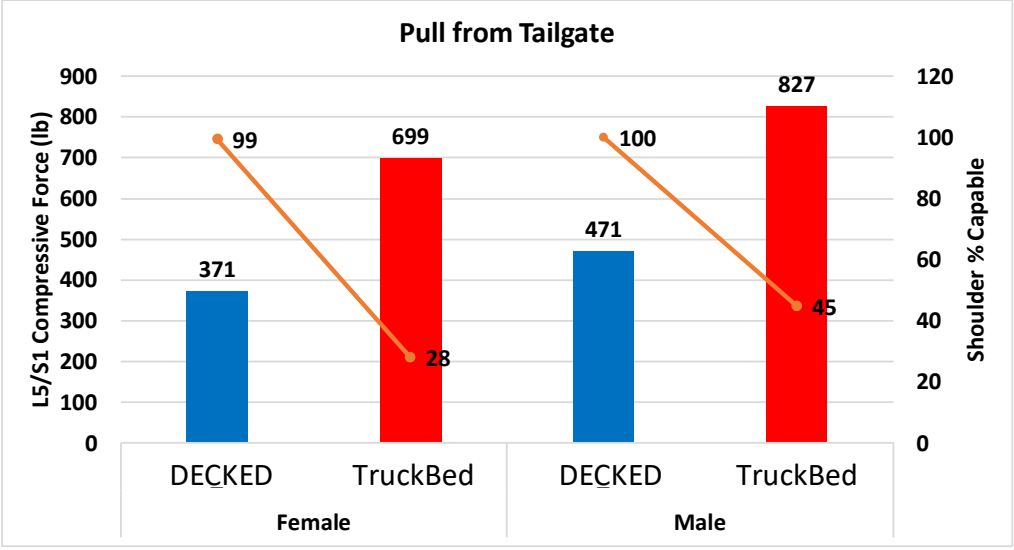


Figure 6 - Stress reductions from pulling DECKED drawers vs. sliding objects across truck bed.

The decision tree illustrated in Figure 7 highlights the hazards avoided when a DECKED drawer system can be used to access objects in an ergonomic posture, without entering the work vehicle. Two scenarios, one with the DECKED drawer system and one without can be conceived where multiple hazardous tasks can be reduced or eliminated using the DECKED drawer system. A major assumption in this approach is that the object placed in the work vehicle is able to fit into the DECKED drawer system. The dimensions of the drawers limit the size of objects that can be stored by volume and weight. The sequence of tasks that may occur is largely a function of whether or not the DECKED drawer system can accommodate the size and shape of the object in the cargo space. Consequently, the weights of many objects that can be stowed in the DECKED drawers that were used in this study ranged between 3-15 lbs each. The larger and heavier items were stored on the DECKED drawer system surface, increasing the vertical reach height by 12" over the truck bed deck height. The risk scores associated with each scenario were adjusted to account for the number of hazardous movements that could be reduced by making the object accessible from the ground using the DECKED drawer system.

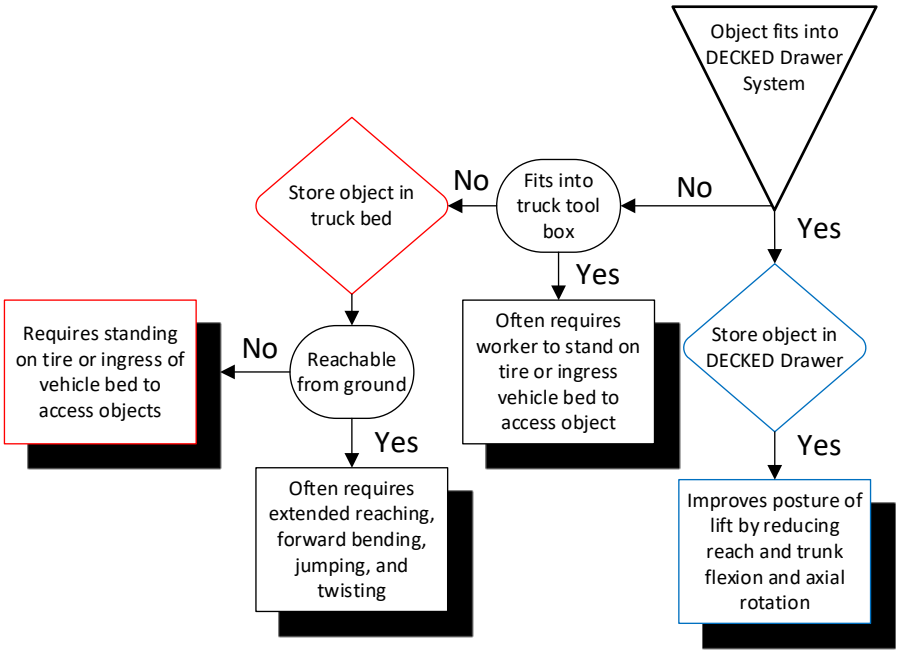


Figure 7 - Decision tree leading to change in ergonomic risk based on how/where objects are stored in a work vehicle using the DECKED drawer system.

The truck bed storage volume for a late model Chevrolet Silverado with a 6' 6" box is 61 ft^3. The DECKED drawer system provides 10.8 ft^3 of storage across both drawers.

The DECKED drawer system outperformed the traditional Toolbox system in safety performance as

measured by REBA. If the object in the bed was retrievable in a drawer, this eliminated the stressful and hazardous task of first climbing into the vehicle, and then either descending with the object, or placing the object in a reachable location prior to egress, followed by a lift from the bed or tailgate.

The posture of the lift performed also improved by reducing trunk flexion and axial rotation, which lowered back compressive force and risk of lifting related low back pain. Jumping from the height of a typical truck tailgate can increase the joint and back loads by over 400%.[5]

The probability of falls from height are also reduced because the number of times an employee climbs into and out of the truck is reduced when objects are retrieved from the DECKED drawer system. The frequency of these events is specific to the industry or trade and could not be estimated for this report. However, in simulation, if 42% of the truck bed's usable storage space is unreachable without jumping and reaching from the side of the bed, climbing onto a tire, or climbing into the bed from the tailgate (see Figure 8) the DECKED drawer system reduces the percentage of unreachable cargo space to only 18.6%. This represents an increase in accessible storage with reduced ergonomic risk by nearly 44% by not requiring unsafe acts and hazardous postures to manually handle objects located in the unreachable cargo space.

The DECKED drawer system could reduce the exposure to fall hazards and the exposure to high joint loads experienced during egress by 16.7% because the lifting zones marked with the Blue arrows in Figure 8 are less hazardous than the other zones and activities requiring ingress, jumping and reaching from the side (Green arrows), or standing on a tire to access the objects in the light red, marked area.

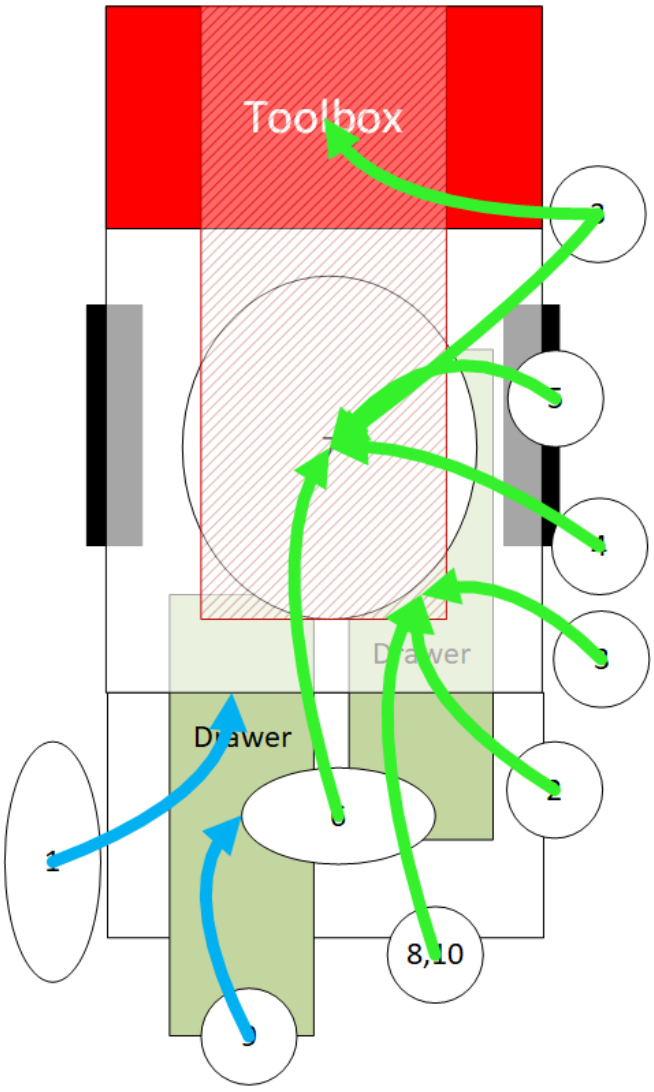


Figure 8 - Reduction in Hazardous Tasks when DECKED drawer system is utilized. Blue arrows indicate tasks when objects are stored in the DECKED drawer system and do not require extended reaching, jumping or ingress into the truck bed to retrieve the object.

Influence of added height using the DECKED drawer system. The surface height of the DECKED drawer system is 12" above the truck bed deck. If the vertical starting height of a manual lift is 35" (represents a reasonable height for a truck bed) and the vertical position of the hands at the origin of the lift was raised to 47", this only represents a reduction in the recommended weight limit by about 5 lbs according to the NIOSH revised Lifting Equation[8]. A reduction of 5 lbs when lifting with two hands from the side or rear of the vehicle in this posture would not significantly increase the biomechanical stresses on the back and shoulder. When lifting from the side of the truck, the added height of the DECKED drawer system increased reachability of objects and improved access for shorter employees. This advantage provides a meaningful difference for shorter employees, allowing some objects to be grasped and lifted from the ground that would otherwise be unreachable. An illustration of the Zone of Convenient Reach found in Figure 5 shows how the additional 12" of height allows the employee to reach objects further away without bending the trunk.

Summary

A comprehensive biomechanical analysis and risk assessment of the typical awkward conditions in the work vehicle environment using the DECKED drawer system was performed to quantify ergonomic risk. The DECKED drawer system created a safer work vehicle environment by providing greater access to objects that could be stored in otherwise unreachable locations in the vehicle storage volume. These objects became reachable without increasing ergonomic risk or requiring an employee to ascend to the elevated work surface or jump and reach to grab objects from the ground. The reductions in physical exposure measured while using the DECKED drawer system represent values consistent in other industries that have shown significant reductions in MSD cases where ergonomic interventions have been implemented as controls.

List of Findings

- The ergonomic risk of manually handling objects while loading and unloading the work vehicle showed a marked reduction in REBA score for objects that could be placed in the DECKED drawer system.

- The elevated surface of the DECKED drawer system increased accessibility to objects in the storage volume without the need to stand on a tire or jump and reach from the side of the vehicle.

- Organizing a work vehicle environment using the DECKED drawer system as evaluated in this study resulted in a reduction of physical exertion and ergonomic risk measured using REBA, BCF, shoulder and elbow moments for tasks that would otherwise require excessive forward bending, reaching, and twisting to manually handle objects located within reach from the ground.

- The DECKED drawer system improves the "fit" between the work vehicle environment and the employee, providing employees with lower strength and shorter stature safer access to objects stored in the work vehicle.

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