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A Comparison of Force Demand Measurement Methods while operating a Lift-assist during Automotive Assembly

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By

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ABSTRACT

This Master Thesis raise on from the necessity to evaluate the method currently used within the FCA industries in order to assess the forces demand on an assembly line worker that has to use a lift assist device to perform his job task.

To reach this aim an Instrumented Handle has been employed in order to directly and in real-time record those forces during an actual work shift in a FCA assembly plant. One of the milestones of ergonomics has been always to look at the real exertions, actual postures and exact movements performed by the workers on duty. The Instrumented Handle Method allows recording the real forces exchanged at the hand-handle interface during a real job task performing without introducing any corruption, approximation or modification usually introduced by job-simulating standard measurement methods.

This study through data analysis and processing has been able to evaluate the actual standard FCA method showing the limitations of this procedure, to show the potentialities of the Instrumented Handle Method and to give suggestions for possible future improvements.

“There are no strangers here;

Only friends you haven't yet met.”

William Butler Yeats

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LIST OF ABBREVIATIONS/SYMBOLS

3DDHM: 3-Dimensional Direct Handle Measurements

AGC: Automated Guided Carrier

FCA: Fiat Chrysler Automobiles

FID: Force in Intended Direction

LBD: Low Back Disorders

MMH: Manual Material Handling

MSD: MusculoSkeletal Disorders

OICA: Organisation Internationale des Constructeurs d'Automobiles

OP: Operator

SIS: Shoulder Impingement Syndrome

STD: Standard method

ST_n: Sub-Task “n”

WS_n: WorkStation “n”

WS_nST_m: Sub-Task “m” on WorkStation “n”

1. Introduction

1.1 Background

Manufacturing industries are globally recognized as one of the most important and powerful entities for country's economy. Among them, the automotive industry is one of the strongest and most influential in terms of profitability, innovation and employment opportunities. Aside from engineering and design, automotive companies require a large manual-labor/manufacturing workforce to assemble their products. This workforce is required to perform physical tasks to install, move, secure and place various components using various force efforts at various frequencies all requiring various body postures. The physical burden on the human workforce due to the combination of these different factors leads to workplace injuries. Medical and indirect costs of occupational injuries must not be underestimated: it has been proven that they are at least as large as the medical costs of cancer (Leigh, 2011). To combat the issue of occupational injuries, workplace ergonomics, discipline that aims to fit workplace conditions and job demands to the capabilities of the working population, is employed with the main goal of reducing injury risks (Cohen et al, 1997).

The automotive assembly workforce is often required to perform Manual Materials Handling (MMH) tasks, and these tasks have been shown to cause physical stress mainly on the workers' low-back and shoulders. Manual materials handling represents the 35% of total workers' compensation claims (Trebilcock, 2007) and low-back and upper extremities related injuries account for 44% of all claimed workplace injuries (Trebilcock, 2007).

Heavy lifting, carrying, forceful pushing and pulling are all related to risks of musculoskeletal injury in the low-back and shoulders region. The implementation of mechanical devices to reduce the physical load is a very common and well-known strategy (De Looze et al, 2001). Along automotive assembly lines the introduction of lift assist devices is the most widespread technological solution to reduce the physical load on the worker. The success of these products depends not only on the device itself but, on the process of product development and implementation (De Looze et al, 2001); the effectiveness of the intervention must be checked often in order to determine the long-term functionality of the implementation (Van der Molen et al, 2005). Introducing a mechanical lift device is not always a definitive solution. Successfully reducing a specific load parameter in a specific activity may generate negative side effects as low-back or upper limbs injuries occurrence (De Looze et al, 2001). De Looze et al (2001) analyzed different uses of lift assist and found that some succeed in eliminating the stressful activity (usually lifting) through a complete mechanization of the work without any negative side-effects, while others only transferred the physical demands from the low-back (removing the heavy lifting operation) to the upper extremities.

To determine the risk level of injury associated with a certain workstation design, the required tasks are analyzed from an ergonomics perspective. In the most basic explanation, the ergonomic analysis will determine the ratio between the physical demand(s) associated with the workstation tasks and the actual physical capacity of humans (Potvin, 2014). In order to estimate the injury risk, a highly accurate measurement of the demand is needed to then be compared to well establish worker capacities. An accurate measurement of the physical demand can be achieved using advanced measurement tool directly on the workplace. In this way, all the approximations commonly introduced in a laboratory research work or in off-line measurements are mostly avoided.

1.2 Statement of the purpose

The purpose or the current study is to evaluate the current standard FCA method to measure force demands required to operate lift-assist devices used during automotive assembly. This evaluation will be completed by comparing the results obtained through a single axis compression hand-held force transducer (Standard Method) to the ones obtained using an innovative instrumented lift-assist handle methodology, currently not utilized within FCA, that measures applied hand forces in 3 dimensions in real-time during normal assembly line operation. The data have been obtained during daily operations in an FCA automotive assembly plant all in an effort to determine best practices for force effort measurements and possible future improvements to ergonomic workstation evaluations.

1.3 Hypothesis

1) *The calculated difference between the measured peak forces independent of task type will result in statistical significant differences.*

Performing a peak forces comparison, it will be shown that there are differences in the measured forces measurements; such that the instrumented handle method will reveal as more accurate than the hand-held dynamometer method, independent of task type. Koppelaar and Wells (2005) assess five different methods to quantify hand force, concluding that direct on-field measurement methods are the most reliable. Furthermore, peak forces recorded with the instrumented handle are expected to be greater than peak forces recorded with the standard methodology.

The expected difference in the results obtained with the two different methods would be related to three different aspects. Firstly, forces are three-dimensional in nature and a precise measurement can be achieved only through a multi-axis measurement method (Korkmaz et al, 2013); a single axis dynamometer will certainly introduce inaccuracies. Secondly, workers perform oblique movements while using a lift-assist device; these are approximated by the ergonomists employing the standard methodology as standard movements (push, pull, lift and lower) losing part of the real information. Thirdly, considerable initial forces are required at the motion starting and ending forces are necessary to decelerate the component (Van der Beek et al, 1998); these forces are called inertia forces, and they are mainly neglected by the standard measurement method.

2) *The integrated forces analysis will show, with statistical significance, a difference in the physical demand will exist between different workstations.*

Each lift assisted workstation requires a different type of lift hoist based on mass, dimensions and shape of the part to be installed. Based on these variables, it can be forecasted a different physical demand between different workstations; however, using the integrated force analysis will be possible to have a wide understanding of the physical effort required. Differently from a peak force analysis, the force integration along the cycle time is representative of the total amount of forces required to perform the whole task. In brief, workstations are differently designed to lift/move weights, and the integrated force analysis will show that different physical demands are required.

3) *The integrated and peak forces analyses will show that a statistically significant difference in force demands can be present between different operators for the same given workstation.*

The sequence of sub-tasks required to complete a job task on a specific work-station is pre-fixed. Whereas, workers can complete job tasks using different movements/strategies. Moreover, the worker anthropometry data (height and weight) and the worker physical capacity lead to different movements and therefore to different measurements of the physical efforts exerted. Furthermore, the worker level of experience could play an important role as well. Workers gain experience while working in a manufacturing environment and individual performance are progressively improved (Argote and Epple, 1990). As a result, it can be predicted that an experienced worker will perform the job task in the most effective ways under the standpoint of both productivity and physical demand required leading to smaller values of the actual forces exchanged between worker and machinery. In this study would only be possible to correlate differences between workers to differences in moving strategies but not to factors like level of experience or anthropometric data. However, for certain sub-operations different force exertions between different workers will be statistically shown.

2. Literature Review

2.1 Workplace Injuries and Work related Musculoskeletal Disorders

Work related Musculoskeletal Disorders (MSD) are major concern for both society and companies as they produce burdens on both from a financial and wellness perspective. The following sections will discuss MSD's and the negative consequences that they produce.

2.1.1 Common work related injuries reported

According to the "Bureau of labor statistics" of the US department of labor in the 2015 in the USA, between private industry, state government and local government, there were 4,836 cases of fatal injuries and 1,153,490 days-away-from-work cases. While according to the Association of Workers' Compensation Boards of Canada, 852 workplace deaths were recorded in the country in 2015, and 232,629 work-related injury or disease. From these data, it is clear that much attention is required on work-related injury whether worst case, fatality, or non-fatal as MSD's.

When discussing MSD's we must understand that they can occur along the different parts of the body according to the task performed and, can be attributed to the design of the task which effects the way in which it is performed. However, it is well known that the most common injuries related to MSD's are related to the low back and shoulder. In fact, in the US in 1989, the three major American automotive companies at that time (Chrysler, Ford and GM) had to face workers' compensation costs of $ 11.4 billion for low back injuries and $ 563 million for upper limbs injuries as arms and shoulders (Laura Punnett, 1999). Since these two types of injuries were and are the most claimed, most of the effort is spent focused on the low back and upper limb.

2.1.1.1 Low-back injuries

The human spine is comprised of vertebrae with intervertebral discs between each vertebral body. The intervertebral discs are made up of three different types of tissues: nucleus pulposus, annulus fibrosus and cartilage endplate (Michael A. Adams, 2015). The nucleus pulposus is the soft deformable central region of the intervertebral discs and it is composed mostly of a proteoglycan gel held together loosely by a sparse network of collagen fibrils. The annulus fibrosus tissue forms 15–25 concentric lamellae that surround the nucleus; each lamella is made of parallel arrays of collagen fibers and surrounded by a proteoglycan gel. The cartilage endplate is composed of hyaline cartilage and it forms a thin layer between the disc and adjacent vertebral bodies conferring rigidity to the intervertebral discs (Michael A. Adams, 2015).

From a mechanical viewpoint, the disc can be considered as an elastic interposition between solid parts, the vertebral bodies, and acts as a functional unit that keep separated the vertebrae, avoiding their contact that would result in a very painful situation for the subject (Marras, 2000), this design of two rigid bodies is considered a joint. Moreover, intervertebral discs are deformable and allow small movements between adjacent vertebrae providing reciprocal mobility for spine flexion/extension, right and left lateral bend and axial twist. Intervertebral discs have also the function to evenly distribute the load on to the vertebrae being able to sustain large compressive forces. So, they are stiff enough to sustain compression loads and distribute them efficiently but, can also work as small shock absorbers giving the ability to the spine to dissipate small amounts of energy (Michael A. Adams, 2015).

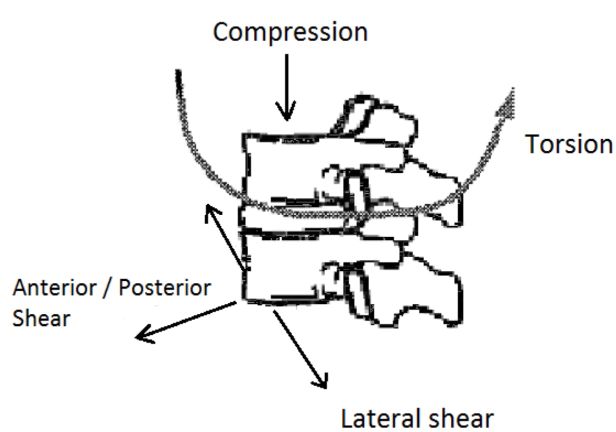

Figure 1. Three-dimensional loading on the back spine (Adapted from Marras, 2000)

The spine can be subjected to different types of stresses (forces), loading can occur in three different axes: compression, shear and torsion as shown in Figure 1 (Marras, 2000). Due to these three forces, working either independently or together, the intervertebral discs are subjected to deformation and/or repetitive deformation that have been linked to discs degeneration (Marras, 2000).

The degeneration basically consists in ruptures in the annulus fibrous that is translated in a diminishing of its resistance to mechanical strain. Carl Hirsch (1951) found that ruptures in the dorsal area of the lower lumbar discs were very common in cases of disc degeneration, which ultimately leads to low back pain. It has also been proven in the same study that the degenerate discs are no longer able to recover their normal function capability and after an injury it is possible that even slight strains produce pain (Hirsch, 1951).

Low Back Disorder (LBD) represents the leading MSD in the United States and one of the most common in the world of manufacturing industries. To testify this statement with numbers it can be said that according to Marras (2000) up to 80% of American adults experience back pain during their life and, 4-5% of them have an acute low back pain episode every year. Andersson (1998) has confirmed this thought through epidemiology evidence of low back pain by identifying 75-85% of the workers' experience LBD at least once in their lifetime (Andersson, 1998). Most of LBDs have been related to manual material handling tasks and lifting tasks and, the level of causal correlation between the work physical risk factors and MSD is shown in Table 1 (Marras, 2000).

RISK FACTOR	Strong Evidence	Fair Evidence	Insufficient Evidence	Evidence of no effect
Lifting movement	++++			
Awkward posture		++		
Heavy physical work		++		
Whole body vibration	++++			
Static work posture			0	

Table 1. Evidence for causal relationship between risk factors and MSD (table adapted from Marras, 2000)

Furthermore, Marras (2000) recognized a correlation between LBD and age and behaviors of the workers, establishing that the highest frequency of symptoms usually occurs in workers relatively young, between 35 and 55 old, and factors such as smoking or obesity are strongly contributing to injury occurrence (Marras, 2000). While it is understood that forces experienced within a low back joint, especially large in magnitude, increase the risk of injury, accurately calculating these magnitudes is difficult as they require expertise in biomechanical modelling, which requires full body kinematic and kinematic data. Also, Norman et al. (1998) identified four different factors; peak torso flexion velocity, the integrated lumbar movement, the peak and cumulative spinal load strictly correlated with low-back injuries occurrence and reported that a high level of exposure to them would translate in a higher risk of low back disorders.

2.1.1.2 Shoulder injuries

Research has proven that shoulder injuries are the second most common injuries in manufacturing plants after low back injuries. According to Punnett et al. (2000) from work studying automotive assembly, the annual incidence of shoulder disorders was 84 per 1000 workers per year or $2/3^{rds}$ of reported LBD found from the same data. In the Punnett's study the mean age of those with reported shoulder incidences was 39, and according to Eira Viikari-Juntura (2010), shoulder injuries are strongly related to the age such that they are not common for those younger than 40 years but do increase with the age, where a person is four times at risk when they are 50 years or greater.

The shoulder is a complex mechanism which is comprised of various structural human tissues, but by design is the most mobile joint in the human body. The shoulder is made up of: the ball-and-socket joint, made of a ball-shaped bone, the humerus, that fits into a cup-like hollow bone, the scapula, allows for motion in all planes. This joint is surrounded by a fibrous sleeve, which helps to hold the joint together. A group of muscles and tendons make up the rotator cuff, which controls the shoulder movements and along with the fibrous sleeve, helps to hold the joint together. The most common disorder of the shoulder, accounting for 44-60% of all complaints about shoulder pain is the degenerative degradation of the tendons of the rotator cuff, (Van Rijn et al, 2010) this phenomenon has defined as Shoulder Impingement Syndrome (SIS). This syndrome results in pain, weakness and loss movement capability at the shoulder. The exposures to stressful factors such as repetitive movements, vibrations or, heavy lifting are considered risk factors associated with SIS. When exposed to these factors, the tissues of the joint are at great risks of mechanical wearing, and due to the its low capability to recover from such mechanical distress, disorders may not present themselves for many years (Viikari-Juntura, 2010).

Punnett et al. (2000) showed that the optimal flexion angle (angle made from the arm moving outwards in front of the trunk and shown in Figure 2 is less than 45 degrees, where mild flexion from 46 to 90 degrees that can be acceptable for short periods of time, and severe flexion angle greater than 90 degrees should be always avoided. While shoulder angle recommendations may be slightly different depending on the literature, 90 degrees of shoulder flexion is commonly considered as severe flexion, and must be avoided to prevent fast fatigue and consequent injuries (Punnett et al, 2000). In fact, according to Viikari-Juntura (2010), when the shoulder angles are greater than 30 degrees the blood supply to the muscles starts to be compromised and this could enhance injuries occurrence.

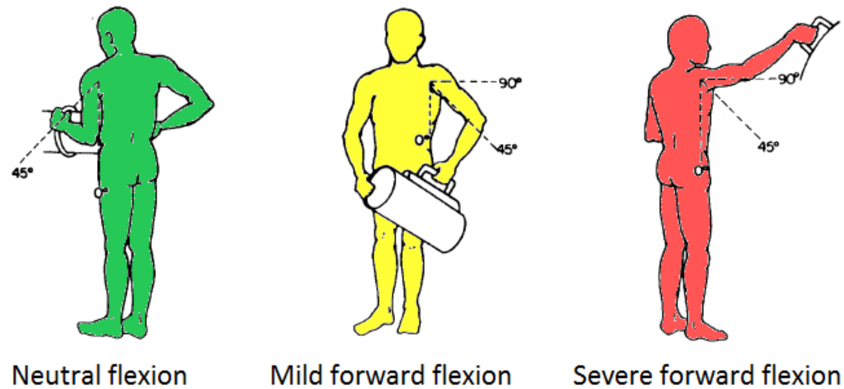

Figure 2. Shoulder standard postures classification (pictures taken and adapted from Punnet et al, 2000)

In automotive industries, arms are the most used part of the body for the workers and shoulder due to this, it has been found that in average the shoulder are in a mild-flexed position for about 25% of the cycle time and, in a severe-flexed position for more than 10% (Punnet et al, 2000). This fact and the high dynamic postural demand, that has been recorded in up to 35 posture changes per minute, has been identified as the biggest responsible for shoulder injuries in manufacturing (Punnet et al, 2000). In fact, Svendsen et al. (2004), in their cross-sectional study of work-related injuries, concluded that a strong relationship is present between work with elevated arms and clinically verified shoulder disorders.

2.2 Importance of Workplace Ergonomics in Automotive Manufacturing

Ergonomics, the study of human-machine interaction strives to determine the optimal combination of task demand and human capability to positively impact the worker and the employer. Effective ergonomics plans will aid in the ideal designs to create work situations in which workers can safely and efficiently work. The term "design", as Lamonde and Montreuil (1995) explain in their study, must be intended in its largest sense, as ergonomists must be involved in both design new work situations and re-design existing ones. Ergonomics has led to continuous improvement always towards the best possible working configuration.

Historically, the industrialization process has required the worker to adapt to the tasks demands of their work; however, we now understand that the opposite of this should be achieved. At this purpose, as Jan-Erik Hansson (1988) suggests, ergonomics should be brought inside and applied in all the different manufacturing areas. These fields of application could be listed and summarized as follow:

- Workplace organization: while designing a new plant the position of each workstation and the tasks should be considerate. These have usually great consequences on the work.
- Machinery design and purchasing: a well-designed tool or machine will aid to reduce the physical demand on the worker, and thus reducing the risk of injury.
- Standardization: a standardized process leads to the generation of jobs that increase the presence of repetitive operations, this should be avoided when possible as repetition has been linked to an increase of risk of injury.
- Education and training: worker training and educational focusing on ergonomics concepts will aid them in identifying risks that can cause them harm at the workplace. Moreover, a strong interaction between worker and ergonomics experts should be encouraged to generate an effective transfer of worker knowledge to those designing the tasks.

2.2.1 Relevance of automotive manufacturing industries in North America and Europe

The automotive manufacturing industry has always been one of the most important and productive industries in the world, especially given the fact that it employees thousands of workers all over the world. According to the Organisation Internationale des Constructeurs d'Automobiles (OICA) in the USA in the 2015 produced 12,100,095 cars, 2,283,474 in Canada and 1,014,223 in Italy (Table 2). It has been estimated that in 2016 in the USA alone, Bureau of Labor Statistics, total number of workers in the automotive industry was 934,000. Across the globe, countries like

Germany, Japan, South Korea and Canada strongly depend on automotive industries; moreover, in some areas or regions of these countries those industries represent the most important source of earnings for local habitants.

COUNTRY	VEHICLES PRODUCED IN THE 2015
EUROPE	21 096 325
Germany	6 003 164
Spain	2 733 201
France	1 970 000
United Kingdom	1 682 156
Russia	1 384 399
Turkey	1 358 796
Czech Republic	1 303 603
Italy	1 014 223
Slovakia	1 000 001
AMERICA	20 964 654
Usa	12 100 095
Canada	2 823 474
Mexico	3 565 469
Brazil	2 429 463
ASIA	47 786 156
China	24 503 326
Japan	9 278 238
South Korea	4 555 957
India	4 125 744
AFRICA	835 937
TOTAL	90 780 583

Table 2. Vehicle production numbers in 2015 according to the Organisation Internationale des Constructeurs d'Automobiles correspondents survey (OICA, 2015)

2.2.2 Needs to avoid injuries for economic reasons

Companies strive to reduce waste in all aspects of their organizations that will allow them to be competitive and profitable. Workplace injuries have been identified as costly to companies and if not well controlled, they can be detrimental to their monetary goals. This is a major reason for companies to invest in ergonomics, along with the desire to maintain a safe working environment for their employees.

2.2.2.1 Costs related to injuries

Type of injury	# of events	Percentage	Costs in $ billions	Percentage	Average cost per injury
Non-fatal injuries					
No days away from work	6 084 086	71%	$ 5.68	12.3 %	$ 935
1 to 4 days away from work	934 049	10.9 %	$ 0.87	1.9 %	$ 935
Temporary total disabilities	1 020 181	11.9 %	$ 8.21	17.7 %	$ 8 046
Permanent partial disabilities	512 438	11.9 %	$ 8.21	17.7 %	$ 49 925
Permanent total disabilities	8 208	< 0.1 %	$ 5.59	12.1 %	$ 681 615
Total for non-fatal	8 558 962	99.9 %	$ 45.95	99.3 %	$ 5 369
Fatal injuries					
Fatal injuries	5 657	< 0.1 %	$ 0.31	0.7 %	$ 55 595
TOTAL	8 564 619	-	$ 46.26	-	$ 5 401

Table 3. Estimated numbers and medical costs of occupational injuries in US in 2007 (table adapted from J. Paul Leigh, 2011)

As Laura Punnett (1999) proved in her studies, the hidden costs of workplace injuries and work-related MSDs can range from 2 to 3.5 times the workers' compensation costs paid by an employer. Moreover, costs related to shoulder injuries were estimated to average approximately $ 1,851 per reported shoulder disorders (Punnett et al., 2010). While according to the Marras' research (2000), LBDs significantly increase workers' compensation costs: they represent about 33-41% of the total cost of all worker compensation costs. These are just a few examples that help to highlight the monetary burden that MSDs cause for companies (Table 3).

2.3 Ergonomic challenges in an automotive manufacturing plants

The most common ergonomic challenges are explained in the next paragraphs with a focus on heavy components requiring a lift assist hoist used for transporting parts in a manufacturing environment.

2.3.1 Factors associated with MSD's

Within a manufacturing environment MSD's have been associated with the following risk factors (Potvin, 2014):

- Awkward postures that often a worker is required to assume to perform his job;
- High exertion forces to perform tasks;
- Repetitive motions;
- Duration of the work shift, usually around 8 hours, that makes the worker to accumulate fatigue can reduce the physical capability and lead to injuries.

2.3.1.1 Awkward postures

A modern automobile has between 4,000 and 8,000 single different parts depending on the car segment and level of quality. All of these parts require some form of securing to various locations on the vehicle, most often completed by workers. Figure 3 shows a few postures required to perform different tasks during automotive assembly. Awkward postures are often required to perform the job task; the assumption of posture like these can be very harmful for the human body even if force effort is minimal. Awkward postures often necessitate any load held and/or force effort required to be completed far from joint center's or, body segment's center of mass. Each of these can cause a considerable moment demand on the joint leading to muscle fatigue, impairing the muscle capability, all increasing the risk of injury. Viikari-Juntura (2010) revealed that an awkward posture such as hands over the shoulder lead to a poor blood supply; a poor blood supply to the muscles impairs their functionalities reducing their capacity, increasing the possibility of injuries. Awkward postures easily overload muscles, tendons and tissues deeply increasing the injuries occurrence probability (Potvin, 2014). Ergonomics tries to address these issues to make worker assuming more neutral postures reducing in this way their risks of injury.

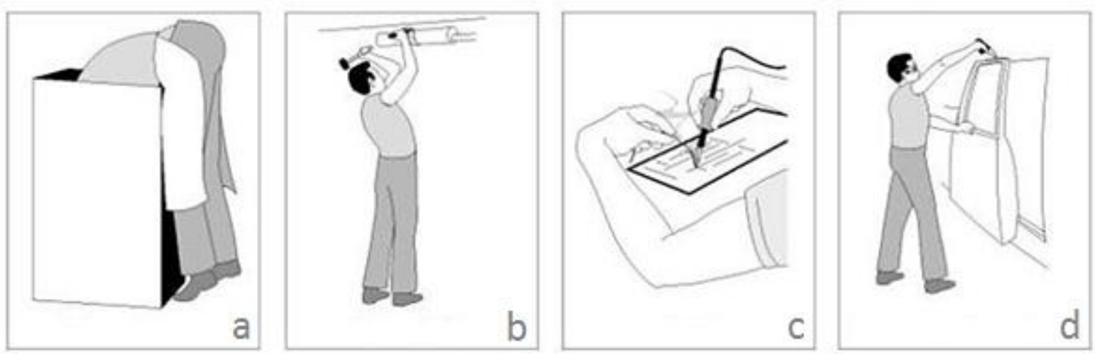

Figure 3. Common awkward postures in a car assembly plant 5a. A worker is forced to bend too much into a box to pick a component 5b. A worker must work holding his arms over his head 5c. An excessive flexion of the wrist is required 5d. A worker assumes a bad posture for his shoulder (pictures taken and adapted from Cohen et al, 1997).

2.3.1.2 Repetitive work

In a workstation, the same operation is performed on a product that is usually moving along the assembly line. In this type of environment, the work pace is not self-chosen by the workforce, and the worker must follow a predetermined pace (Sundelin et al, 1992). The time needed to complete that operation is called cycle time. The cycle time of a workstation can be defined as the amount of time between the start of an operation on a product and the start of the operation on the following product. Usually the cycle times of all the workstations in plant are set to be the same according to the slowest one.

In automotive assembly plant cycle time can range from as little as 30 seconds to as long as 3 minutes. This means that the same operation is performed between 20 and 120 times per hour, which translates to 160 to 960 times among an 8-hour shift. This factor has been identified as increasing the injury risk to workers as it can lead to muscle fatigue, and as fatigue accumulates the force production potential decreases, thus reducing the overall workers' physical capacity (Potvin, 2014). A lesser force can be repeated more often than a bigger force to get to the same level of fatigue and then get injured (Figure 4, Potvin, 2014). Based on this knowledge, a high magnitude of force effort can only be exerted for a limited amount of time and requires considerable time for recovery between efforts. In fact, it can also be stated that a large quantity of low force repetitions does not give enough time to the muscles to recovery and for this fatigue is reached faster (Potvin, 2014).

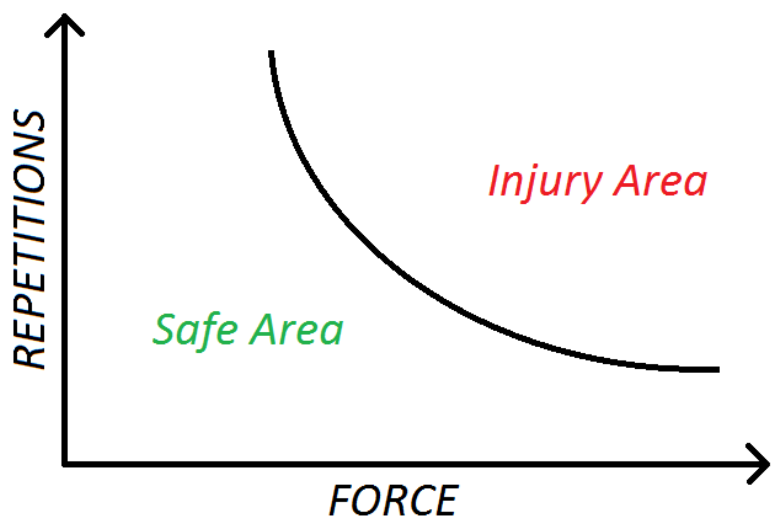

Figure 4. Force exertion level that can be sustained for amount of repetitions (adapted from Potvin, 2014)

2.3.1.3 Work time schedule

A typical North American automotive assembly worker's shift is 8 hours and this occurs for 5 days per week. Depending on the physical demands, these 8 hour shifts cause cumulative muscle fatigue, fatigue which is defined as the reducing in the muscles ability to perform work, can limit the worker ability to meet the physical demands associated with the task, which can increase the risk of injury (Potvin, 2014).

Although workers are provided with recovery time between shifts, approximately 16 hours, it would be naïve to assume all that time is spent simply resting. In addition, recovery time depends a lot on the workers age, this is especially important as a greater disproportionate of older workers are seen within today's workforce (O'Berry et al, 2009). Young workers' ability to recover from fatigue and adapt to work time schedule changes is more likely (Reid and Dawson, 2001). Reid and Dawson study (2001) compared different aged workers on a 12-hour shift, on 4 consecutive days per week. It was found that older workers have more sleep disruption and maladaptation to longer shift work due to their bigger time need for fatigue recovery (Reid and Dawson, 2001). Another study revealed that occupational stress deeply impairs workers sleep leading workforce to encounter mental fatigue and diurnal sleepiness (Eksted et al, 2006).

2.3.2 Heavy component lifting operations

An automobile has many parts that have various masses that require human effort for insertions and transportation, those parts with greater masses may exceed the physical strength capability of humans and therefore, require a device to assist. Forceful effort and precision are the two most important factors needed when a heavy component is required to be positioned to a specific location. The most common solution for moving heavy masses is to employ the use of a lift assist hoist which allows the work to push/pull the mass into position, without the requirement of lifting. There are many different commercially available lift assists currently on the market. In this section an overview of the different types of lift assist and their features.

2.3.2.1 Main functioning mechanism of different types of lift assists

Lift assists are required to be affixed to stable structures within the plant, and this interface can be: floor, wall or, roof. The device can be designed with a single arm or, with many articulating arms along motion in multiple axes. These assists can also be attached to sliding rails that will allow for the translation of the part to different areas of the workstation. However, the main purpose of these devices is to remove the physical demand of the mass of parts and this can be completed by mechanizing the device by: compressed air motors, pneumatic cylinders or, electric motors.

2.3.2.2 Different types of joints

A lift assist device is usually made with articulating arms connected each other through joint design. Movement capability and reachability area of a lift assist device depend basically on the arms configurations and on the type of joint between adjoining arms. Two common joint types are as follows (Figure 5):

- *Rotational joints*: allow the arms to rotate around a certain axis respect to the previous arm; this type of joint can allow a rotation 360 degrees but sometimes a rotation of just a portion of the whole angle is permitted;
- *Linear joints*: allow a linear translation between the two parts that share the joint and usually this type of joint is used at the end effector for reachability reasons.

In reality, the majority of lift assist devices are designed as mixed joints which combine both linear and rotational to optimize for movement, allowing for the greatest reach envelope and ultimately adaptations to various manufacturing tasks.

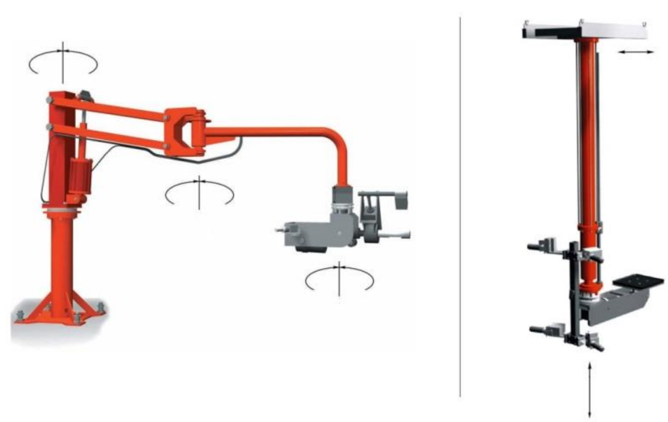

Figure 5. Lift assist device by Ergonomicspartners.com. On the left are shown the rotational movements of rotational joints, on the right are shown the linear movements of linear joints. (Pictures taken by ErgonomicPartners.com)

2.3.2.3 *End effectors*

The end effector is the farthest extremity of the lift assist hoist from the operator, and is part that is used to interact with the part that is to be manipulated. Depending on the part to be moved, there are various end effectors that can attached, allowing for user based design (Figure 6).

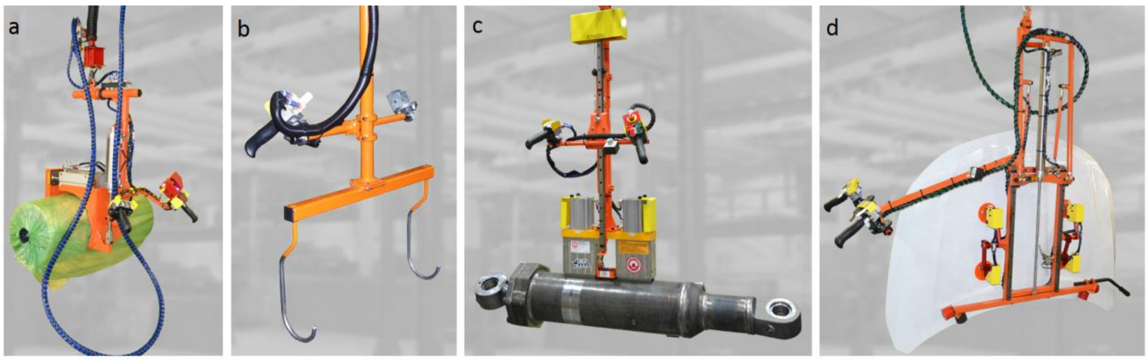

Figure 6. Most common typologies of end effectors available in commerce, pictures taken by the web site of a worldwide operating lift assist producer, www.knight-ind.com.

A different end effector must be mounted on a lift-assist device according to the use that must be done of this machinery. The most common types are:

- Clamp End Effectors (Fig. 6a): provides ability is to grasp parts depending on the inner and outer surface clamp configuration. The Clamp End Effectors applies an inner or outer force to secure the product and are usually specifically designed to each application.
- Hook End Effectors (Fig. 6b): designed to quickly and simply move products, they are useful to quickly connect and disconnect to designated areas of the product. Usually are applied when a straight lift is needed or a simple transfer without manipulation of the product.
- Magnet End Effectors (Fig. 6c): commonly used for picking up metal parts like metal sheets or cylindrical steel tubes. Magnet manipulators maximum capacity can vary depending on the power of the electromagnet and can be differently settled according to the lifting and manipulation needs of each different workstation.

➢ Vacuum Cup End Effectors (Fig. 6d): a solution for handling non-porous or low-porous materials with flat or slightly curved surfaces like glass, hoods, doors or panels. The maximum capacity of Vacuum End Effectors varies according to the load that need to be lifted and the porosity of the surface of the piece that has to be manipulated.

2.3.2.4 Handles

To control lift assist devices a controller is needed, manufacturers use different technologies depending on the industrial application to power the devices (Figure 7). Two common power sources are employed to move the lift assist hoist and controlled at the handle: pneumatic (7a) and electric (7b). Another commonly used solution in devices that are mostly employed in lift operation are the in-line trigger handles (7c), that are putted on the line of lifting and recognize a little change in the forces performed by the worker and help him to lift or lower the weight.

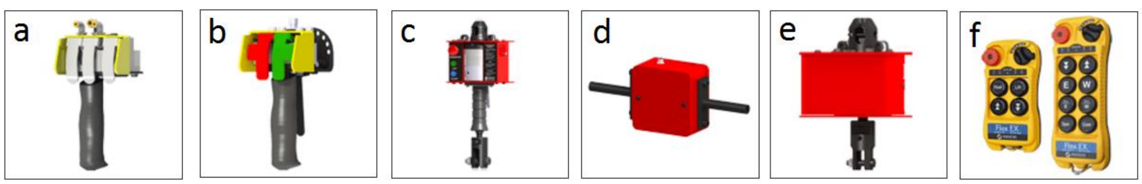

Figure 7. Examples of handles employed to aid in the control of lift assist hoist (www.knight-ind.com/lift_assists).

The newest technology employees load cells (7d) and load monitoring modules (7e) that can recognize small variations in the loads equilibrium due to a small impulse by the worker and help him in the load motion. Another type of controller employed when the worker is forced to work at a certain distance from the piece to move are the wireless remote controllers (7f) that allow maneuvering the lift assist hoist at distance.

2.3.2.5 Issues related to employment of lift assist devices

The overall purpose of a lift assist is to aid the operator in transporting parts from an initial location to a specific destination. When implementing such a device, it is imperative that this solution does not introduce any further ergonomics issues, as in moving the injury concern from one area of the body to another. For instance, when transporting large masses, the acceleration and deceleration associated moving the hoist-mass system should not generate forces greater than human force generation abilities.

Different interventions to reduce the physical work demands associated with manual material handling can have different level of effectiveness. It has been concluded that, in general, when lift-assist devices were part of the intervention , significant reductions in physical work demands and low-back disorders were found (Van der Molen et al, 2005).

2.4 Physical Work Demand

The injury risk associated with any work task can be approximated as the ratio between the actual physical demand to be completed and the physical capacity of the worker required to perform the task (Potvin, 2014).

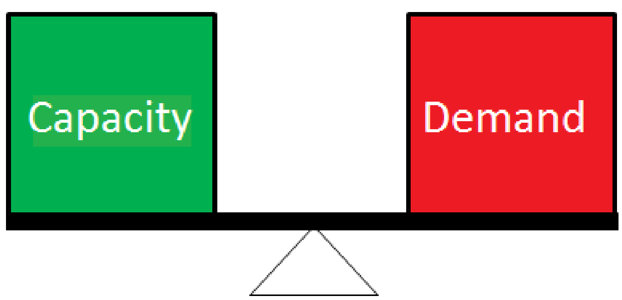

Figure 8. Capacity and Demand balance (Potvin, 2014)

In order to correctly estimate the Injury Risk, physical demand and worker capacity must be measured or estimated with great precision. Bos et al. (2002) aimed to find a universal strategy for specific demands identification of a task. They considered different studies concerning lifting, pushing, and pulling that consider the relation between occupational work demands and, the assessment of the maximum acceptable forces on the workers. From their work, they concluded that it is not possible to formulate a universal strategy to define the occupational physical demands. Therefore, it has been highlighted that attention should be focused on three aspects: the definition of the demand, the assessment of the specific demand, and the quality of the test employed to measure the demand (Bos et al., 2002).

Takala et al., (2010) attempted to identify the published observational methods to assess and evaluate biomechanical exposures in work-places. It has been concluded that although many different observational tools exist, none of the published methods evaluated prevailed on the others in matter of completeness and universal applicability. In fact, it has not been possible to found a methodology objectively better than any others. The ergonomists should critically define their needs and goals; then chose the best method to evaluate the physical demand. The same study suggests some generalized guidelines to select the optimal method: focus on the goals, look at the characteristics of the work task, and consider the individuals involved and the resources available (Takala et al., 2010).

A study conducted by Van der Beek et al. (1998) critically evaluates different methods to measure push and pull forces. Firstly, it has been realized that the external forces can only be assessed with a proper accuracy by direct measurement methods at the workplace level (Van der Beek et al., 1998). Furthermore, push and pull forces were distinguished into three different forces: the initial force required to make the object to start the movement, the sustained force to keep it in movement, and an ending force to decelerate the object (Van der Beek et al., 1998). Then, apart from the intensity of the exerted forces, frequency and duration of the exposure deeply influence the physical demand and therefore, a cumulative/integrated exposure measurement is suggested (Van der Beek et al., 1998). It can be argued that only measuring peak forces is not sufficient to provide the full ergonomics information needed to make the most informed decision. Moreover, the point of application of the force and its direction are necessary to perform a good measurement. Very often it is incorrectly assumed that push and pull forces are purely horizontal, but the resultant force usually also has a vertical component that has to be taken into account (Van der Beek et al., 1998). The combination of various force measurement methods is the best way to achieve reliable results (Van der Beek et al., 1998). McGorry et al., (2004) introduced the use of an instrumented handle combined with a hand dynamometer to directly measure the physical exertion required to a worker during meat cutting. The critical innovation of this research was the trial to directly measure the forces acting on the hand-tool interface. It has been concluded that the actual force of the task is vital in the exposure assessment therefore, for the effectiveness of job modifications (McGorry et al., 2004). In the end, a direct measurement of force and moments can be possible involving hand tools or other sophisticated devices (McGorry et al., 2004). Bao et al., 2009 addressed the issue of quantifying different forceful exertions with different common ergonomics methods like direct force measurement, force-matching and ergonomist estimation based on observation and worker's self-reports. The study results were clear: objective criteria must be preferred, and direct measurement seems to be more sensitive than ergonomists estimations. In addition, Bao et al., 2011 suggested introducing a method of simultaneous analysis of multiple exposure parameters for work related upper-extremity MSD, and then comparing this method with the methods conventionally used. The simultaneous combination method lead to more realistic and accurate information compared to the commonly used method (Bao et al., 2011). It has been proved that multiple instrumentations should be used and combined to achieve a greater comprehensive perspective of the whole job task (Bao et al., 2011).

3. Methods

Study design, involved subjects, instrumentation, data recording, experimental protocol, workstations description and statistical analysis performed for this thesis are described in this section.

3.1 Study Design

The applied forces required by automotive assembly operators to maneuver lift hoists of various designs were assessed through two separate measurement methods:

1. Hand held single-axis force gauge that provides single point peak force data, currently the Standard method (STD) used by FCA ergonomists;
2. Three-Dimensional Direct Handle Measurement (3DDHM) method, an instrumented handle that can replace the right handle of the current lift hoist handle providing time-history force data from three independent axes.

All data was recorded within two FCA North American finally assembly plants. A total of eight workstations that required a lift hoist were selected to obtain the data. For each workstation, the data was captured on three operators while the operators performed their assigned work task during normal production. Additionally, since only one 3DDHM was used and placed on the right handle of all lift-hoist, it was necessary to determine if forces exerted varied from right to left hand. Therefore, on one of the workstations, data were obtained using the 3DDHM from both the left and right handles of the lift-hoist. From the recorded data, the peak and impulse forces were determined. However, the STD methodology required a trained ergonomist to perform each identified sub-tasks during breaks in production, while normal production was not occurring. This methodology recorded a single-axis force data reporting the peak force for each sub-task.

This work compared the results of the force data from each method, from each lift hoist, to determine ergonomic best practices when evaluating the physical demands associated with operations requiring lift-hoists. In addition, the 3DDHM data was used to determine individual differences for force exertion between operators as well as between different workstations.

3.2 Participants

A total of 27 highly skilled FCA assembly operators employed at the North American FCA Assembly Plants, participated in this study. Each participant was the trained operator with the responsibility of using a lift-hoist to transport automotive parts from one area to another. Eight workstations that were equipped with a lift-hoist were identified for the study and the forces required completing each workstation tasks were recorded from 3 operators using the 3DDHM. One of the 8 workstations were chosen to measure the force exertions on both right and left handles from a total of 6 operators, 3 operators performed the task while the right handle was measured, and 3 were recorded from the left handle. Due to privacy issues, we were unable to obtain or report information that could be used to identify each operator (i.e. gender, age, mass, height) however, the participant pool ranged in age between 19 and 65 years.

The person involved in the measurements using STD methods was the trained ergonomist that using the single-axis force transducer tried to determine the peak applied force required for each task.

3.3 Instrumentation and Data Acquisition

To measure applied forces to the lift-hoist two methods were used. First, a commercially available hand-held Force Gauge (Figure 9), this device is the common device used by FCA engineers and ergonomists. This force gauge is a single-axis device that records both tensile and compression applied forces through its end effector, which is attached to the object being manipulated. To operate the force gauge, the user, most commonly a trained ergonomist or, engineer is required to attach the end-effector to the object, ensure the applied force vector is in the intended direction that is used for that task, and then the necessary forces to complete the task are applied. From this, the peak force used task is shown on the digital display, and these values are noted. Since most automotive workstations jobs require many sub-task elements, when evaluating the physical force demands using these hand-held force gauges, each sub-task element requires its own force measurement. All measured forces were organized in a table like Table 4, the magnitude of the applied force was noted in this table along with the type of effort (lift, lower, push or pull).

Figure 9. Example of a Dynamometer used in forces measurements (image adapted from www.aliexpress.com/Digital-Dynamometer-Force-Measuring-Instruments)

	Job Task #			
Sub-operation number	Forces magnitude [N]			
	Lift	Lower	Push	Pull
1				
2				
3				
…				
n				

Table 4. Example of data reporting table for STD measuring method

The second method to measure applied forces was completed using a customized instrumented handle, 3DDHM which is comprised of a 3 axes linear load cell that is attached to the handle of the lift hoist (Figure 10). The 3DDHM allows for direct measurement of the applied forces from the operator, in all three axes, while the operator performs their workstation tasks. In addition, this system is designed to record the force time-history events, rather than a single point of data, which allows for a comprehensive analysis of the entire task. This is quite different than the hand-held force gauge, which only provides single-point data and, the data is not commonly collected by the assembly operator. The 3DDHM has also been designed to replace the handles of most lift hoists.

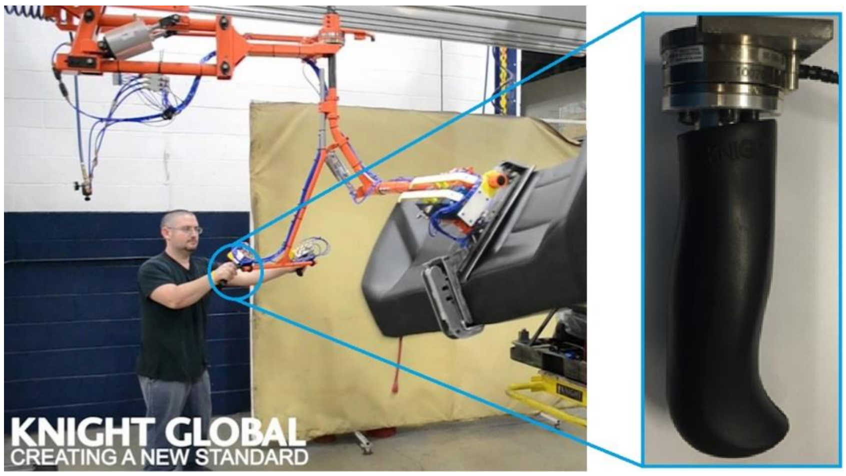

Figure 10. "Knight" lift hoist & instrumented handle (image taken and adapted from www.knight-ind.com)

3.4 Experimental Procedures and Protocol

To measure each workstation, the 3DDHM replaced the right handle of each lift hoist of each workstation. Once the 3DDHM was affixed, the data were recorded as the operators conducted their work duties as they do without any interference or interruption by the researchers. For each workstation, we planned on a total of at least full 20 workstation cycles recoding's from each operator. While this was the target, unfortunately for 8 operators this target was not reached due to uncontrollable circumstances related to plant rotational policies or, other production constraints. Specifically, the lowest quantities of full cycles recorded from one operator was 8 (OP2 on front Cradle positioning) while the highest was 25. The cycles actually recorded per each operator/workstation have been summarized in Table 5. All data were stored on a computer for future analysis.

During a break in production, the ergonomist performed the hand-held force measurements on the identified sub-element tasks. The sub-tasks were identified by the researchers along with FCA ergonomists; each sub-task was identified as a precise portion of the job task during which a well-defined action was performed. These measurements were performed using the STD method; the ergonomist held the gauge and apply forces through the gauge to perform the sub-element task. The gauge will record the peak force required to overcome the inertia of the lift-hoist and these forces were documented.

Cycles Recorded				
Workstation	OP 1	OP 2	OP 3	TOT
Battery installation	25	24	23	72
Dashboard installation	21	22	25	68
FEM_1 installation	25	21	20	66
FEM_2 installation	10	21	19	50
Front Cradle positioning	25	8	18	51
Hard Top loading on AGC	17	19	14	50
Spare Tire (left hand)	25	25	19	69
Spare Tire (right hand)	21	20	21	62
Windshield installation	21	21	20	62

Table 5. Detailed table of collected cycles per each operator per each workstation

3.5 *Workstations description*

Workstations targeted for this research are described sub-task by sub-task in the following chapters.

3.5.1 Battery installation (WS_1)

On $WS_{1,}$ the operator has to move the battery from the loading pallet to the vehicle positioning the component in the proper allocation into the car hood. This job task has been subdivided in 5 sub-tasks:

- WS_1ST_0: Un-racking; the battery is un-racked from the loading station
- WS_1ST_1: Walk & Alignment; the operator carries the battery towards the vehicle, aligns it to prepare to install it
- WS_1ST_2: Installation; the battery is installed on the car in the proper location
- WS_1ST_3: Walk-back; the operator walks back with the empty lift assist device
- WS_1ST_4: Secure of next battery; the operator secures the following battery.

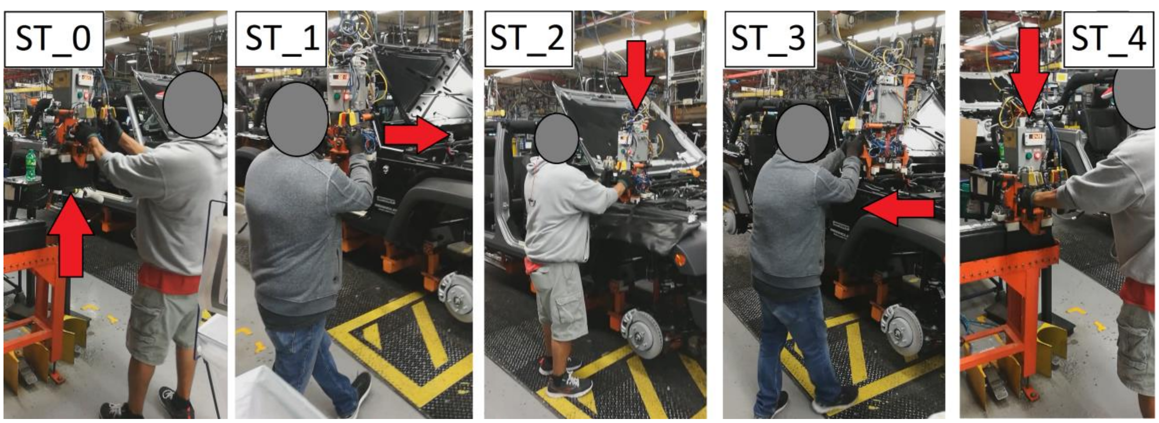

Figure 11. Sub-tasks performed on WS_1; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.2 Dashboard installation (WS_2)

On WS_2, the operator has to obtain the dashboard sub-assembly from the conveyor, and then he has to install it on the vehicle. This job task has been subdivided in 6 sub-tasks:

- WS_2ST_0: Un-racking; the dashboard is un-racked from the carrier
- WS_2ST_1: Rotation; the lift hoist is rotated to prepare the component to be inserted into the vehicle
- WS_2ST_2: Insertion; the component is pushed into the vehicle to be installed
- WS_2ST_3: Installation; the component is installed on the vehicle
- WS_2ST_4: Hoist Extraction; the lift device is pulled out from the vehicle
- WS_2ST_5: Rotation; the hoist is rotated to be ready for the next un-racking

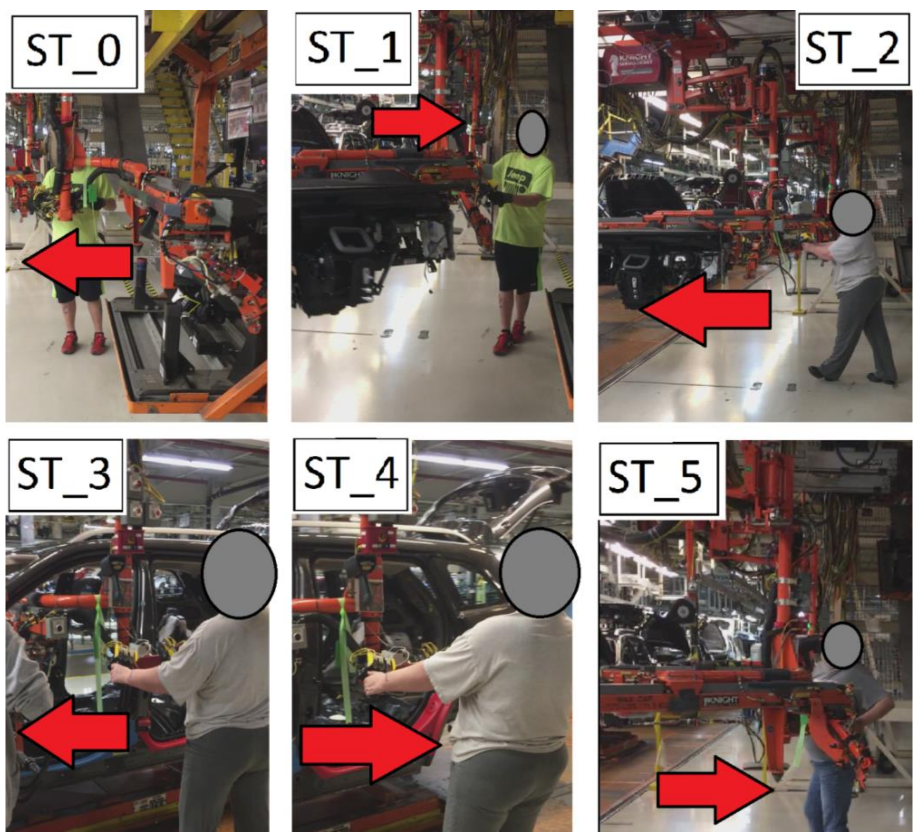

Figure 12. Sub-tasks performed on WS_2; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.3 *Front end module installation – model 1 (WS_3)*

On WS_3, the operator is required to obtain the car front-end module from a conveyor, and then, properly aligning the component, he has to install it on the vehicle. The job task has been subdivided in 5 sub-tasks:

- WS_3ST_0: Un-racking; the front-end module is un-racked from the pallet
- WS_3ST_1: Carrying walk; the component has to be moved and aligned to the front of the vehicle
- WS_3ST_2: Installation; the front end is installed on the vehicle
- WS_3ST_3: Hoist Extraction; the component is released and the lift hoist is pulled back
- WS_3ST_4: Walking; the operator walks back to the pallet for the next un-racking

Figure 13. Sub-tasks performed on WS_3; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.4 *Front end module installation – model 2 (WS_4)*

On WS_3, the operator has to obtain the car front-end module from an Automated Guided Carrier (AGC), and then he has to install it on the vehicle. The job task has been subdivided in 5 sub-tasks:

- WS_4ST_0: Release; the front end module is released on the previous vehicle
- WS_4ST_1: Walk; the operator walks with the empty lift assist device towards the following front end module to be installed
- WS_4ST_2: Un-racking; the component is un-racked from the AGC
- WS_4ST_3: Walk & Alignment; the operator walks carrying the component towards the vehicle
- WS_4ST_4: Installation; the front end module is installed on the vehicle

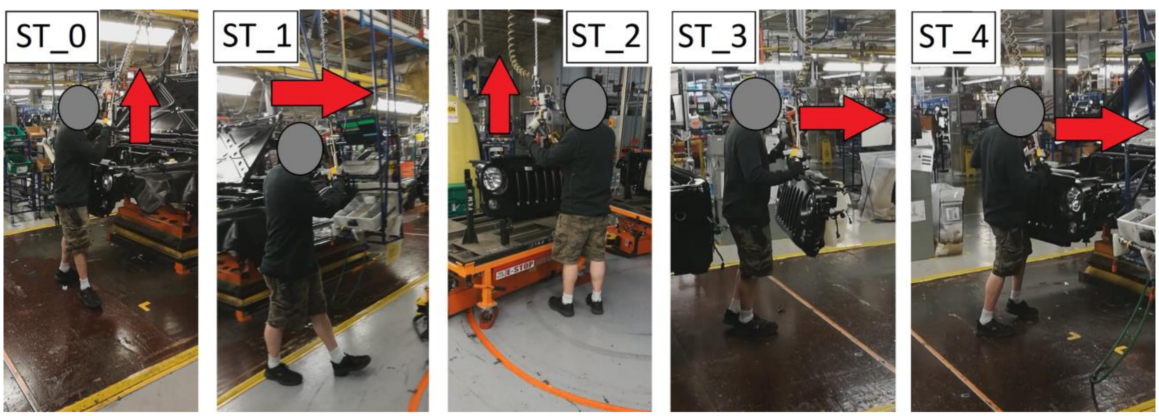

Figure 14. Sub-tasks performed on WS_4; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.5 *Front cradle installation (WS_5)*

On WS_3, the operator is required to obtain the front cradle from a loading pallet, and then he has to position the component on a slowly moving conveyor. The job task done on WS_5 has been subdivided in 5 sub-tasks:

- WS_5ST_0: Un-racking; the cradle is un-racked from the pallet
- WS_5ST_1: Walking & rotation; the worker has to walk pushing the component towards the location in which has to be positioned
- WS_5ST_2: Cradle positioning; the component is lowered down in the final location on a moving conveyor
- WS_5ST_3: Cradle release; the cradle is released when properly positioned and the empty lift hoist is pulled back
- WS_5ST_4: Walking back; the worker walks carrying the empty lift device back to the pallet

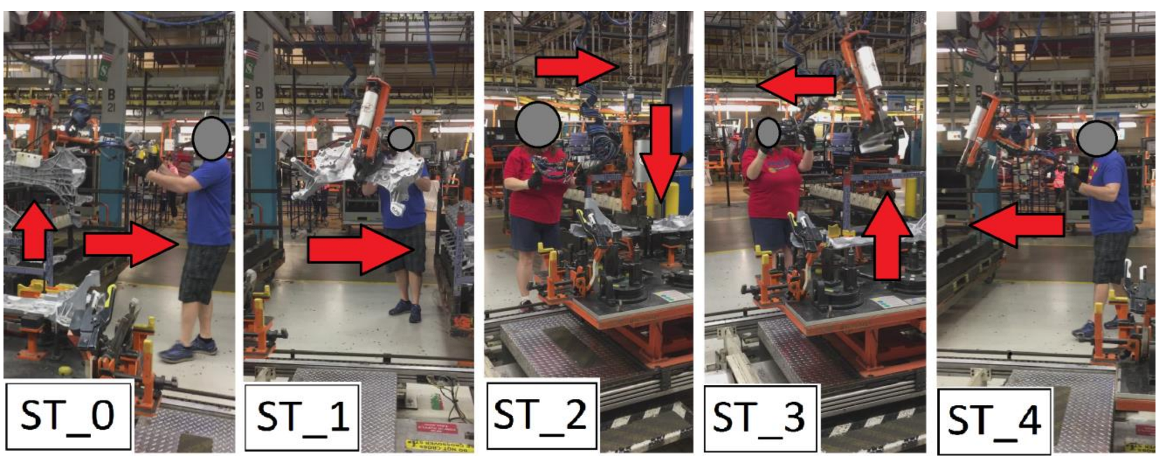

Figure 15. Sub-tasks performed on WS_5; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.6 *Hard top loading on AGC (WS_6)*

On WS_6, the operator has to unload the vehicle hard top cover from a truck trailer, and then he has to position it on an Automated Guided Carrier (ACG). The job task has been subdivided in 5 sub-tasks:

- WS_6ST_0: Loading the AGC; the operator loads the hard top on the AGC
- WS_6ST_1: Pull-back; the operator pulls back the lift assist hoist from the ACG
- WS_6ST_2: Rotation; the lift assist device is oriented in order to un-rack the following hard top
- WS_6ST_3: Un-racking; the hard top is un-racked and pulled out from the trailer
- WS_6ST_4: Rotation and alignment; the loaded lift hoist is rotated and aligned to load the component onto the AGC

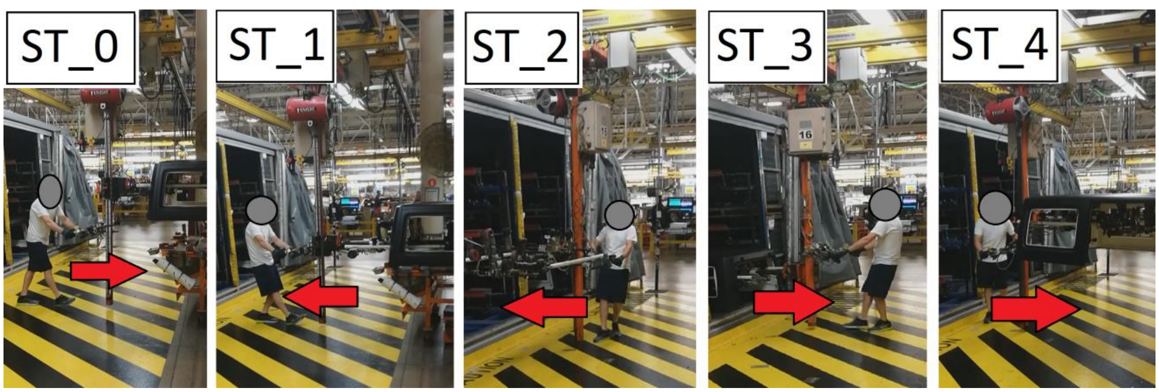

Figure 16. Sub-tasks performed on WS_6; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.7 *Spare tire mounting bracket installation (WS_7)*

On WS_7, the operator is required to install the spare tire mounting bracket directly on the back of the vehicle. The job task done on WS_7 has been subdivided in 3 sub-tasks:

- WS_7ST_0: Push and Alignment; the device is pushed and aligned to the vehicle to be ready to install the component
- WS_7ST_1: Installation; the component is installed on the vehicle
- WS_7ST_2: Pull back; the component is released and the lift assist device is pulled back

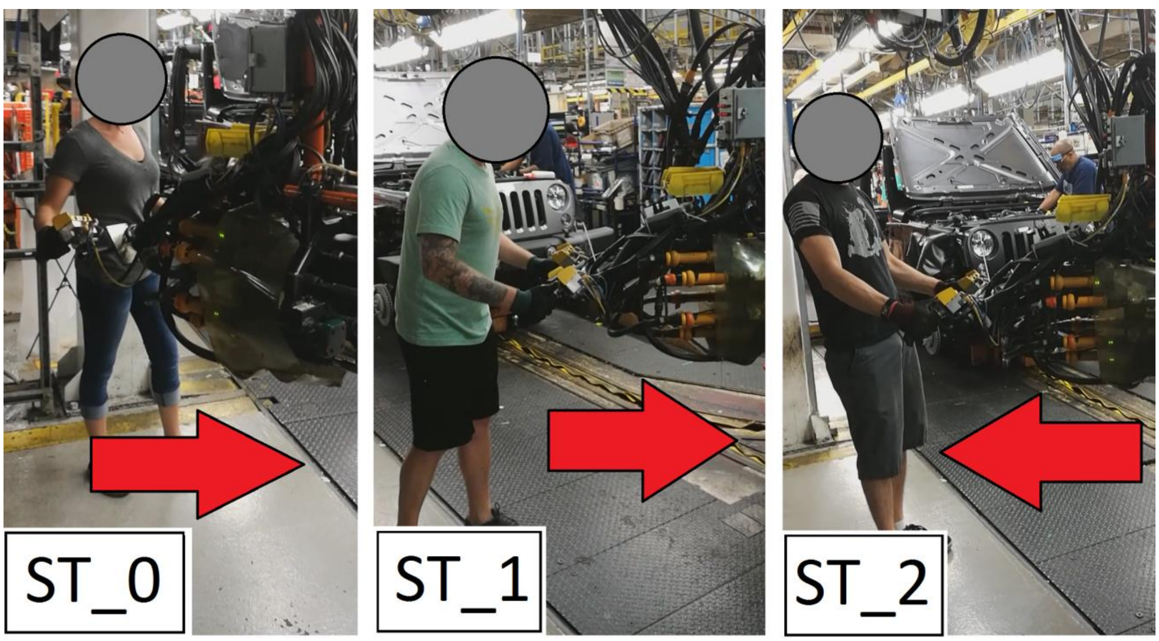

Figure 17. Sub-tasks performed on WS_7; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.5.8 Windshield installation (WS_8)

On WS_8, the operator obtained the windshield component from a robotized arm, and then he installed it on the vehicle. The job task has been subdivided in 5 sub-tasks:

- WS_8ST_0: Walking to Component; the operator walks towards the windshield orienting the device for the following un-racking
- WS_8ST_1: Un-racking; the windshield is un-racked from its location
- WS_8ST_2: Walking to car; the operator walks with the loaded lit assist device towards the car, aligning the component for the installation
- WS_8ST_3: Installation; the windshield is installed on the vehicle
- WS_8ST_4: Release & walk-back; the lift assist device is released and the operator walks back

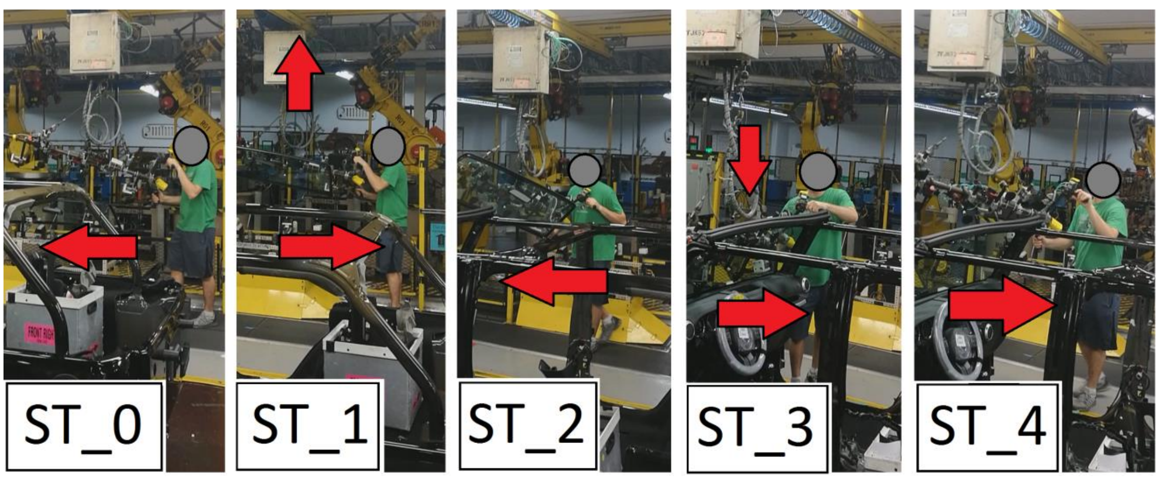

Figure 18. Sub-tasks performed on WS_8; the red arrows represent the principal direction of motion of the component in the identified sub-task.

3.6 Data Processing and Analysis

All analog 3DDHM signals were recorded at a sample rate of 1000 Hz, digitally converted and then low-pass Butterworth filtered (2nd order with cutoff = 10 Hz). On the other hand, the hand-held force gauge used to measure STD peak force has a sample rate of 100 Hz, and no filtering is applied. Since the two recording methods were functionally different; we have conducted processing in order to organize them for analysis. Therefore, since the hand-held force gauge required the researchers to divide each workstation into sub-tasks, to match this method the data from the 3DDHM were divide in the same identified sub-tasks. Furthermore, STD peak forces were collected on one axis while 3DDHM forces were collected on the three elementary axes. In order to obtained a peak force from the 3DDHM data a resultant force was calculated as the square root of the sum of the squares of each force axis (Equation 1). After that, it was identified the peak of the resultant force for each sub-task.

$$R_{xyz} = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

Equation 1. Resultant force as square root of the sum of the squares of single axis forces

It should be noted that forces have only been recorded from the right handle as it was assumed that the forces applied on the handles were symmetrical. Therefore, the recorded peak force by the STD methodology was divided by in half to obtain the force exerted by only one hand. On one workstation (WS_7) forces have been collected on both handles in order to verify the symmetrical assumption.

Figure 19 displays the force outputs on each axis and the calculated resultant from the 3DDHM; this figure also shows and example on how the data were subdivided into each sub-element task.

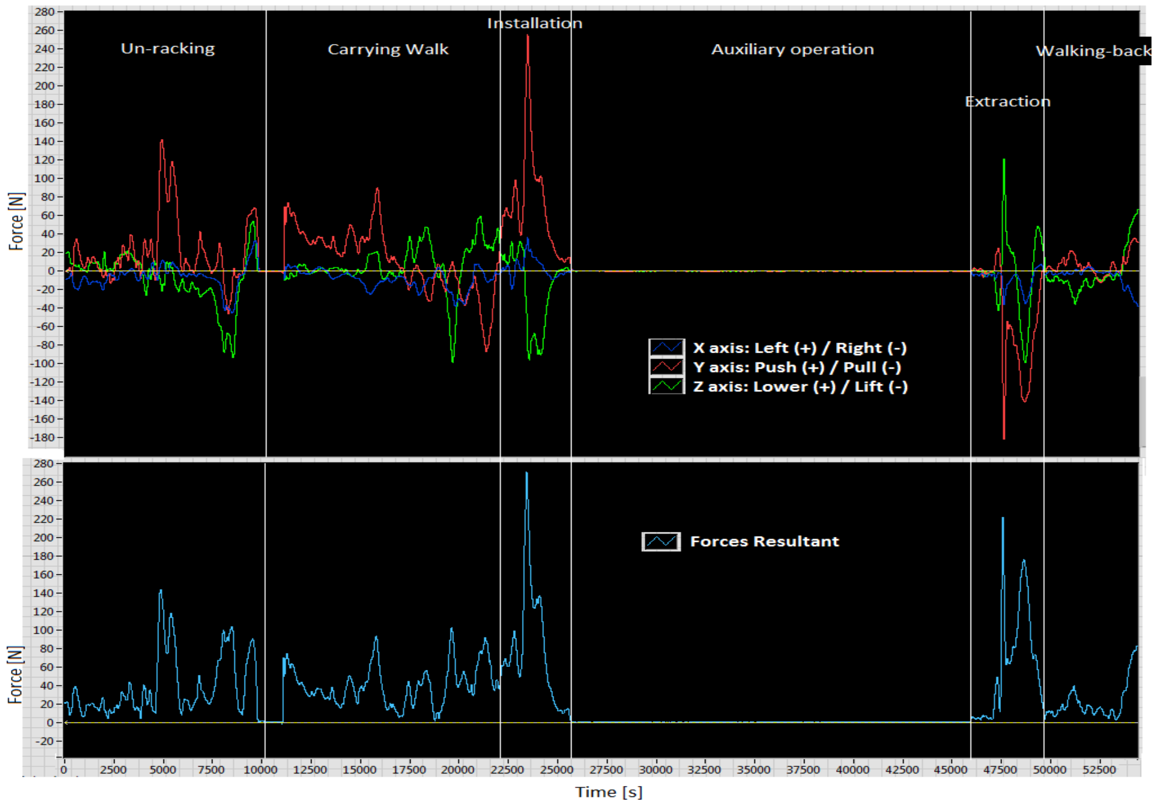

Figure 19. An example of a force-time history output from the 3DDHM of the instrumented handle in which blue, red and green lines represent respectively X, Y, and Z forces, while the light blue line represents the resultant force. The entire job task id also divided in sub-tasks.

Since the 3DDHM methodology collected time-history force data, a calculation of the force impulse, integral of the force-time data, was performed. This type of analysis does not require the identification of each sub-task, and therefore permitted between workstation comparisons of the cumulative effect of force required for each job task to be completed.

Additionally, the 3DDHM data were further analyzed to determine the contribution of each axis (X, Y, and Z) to the peak of the calculated resultant. The contributions were computed per each operator per each sub-task.

3.7 Statistical analysis

In the following chapters the statistical analyses performed in this study are detailed.

3.7.1 Right and left hands 3DDHM Method recordings comparison

To understand whether a difference between the forces applied by different hands exists, both the left and right hands forces were recorded on WS_7. The peak and impulse force data analyses were conducted. Force data were collected on a total of 69 cycles from the left-hand of 3 operators, while the right-hand forces were collected from 3 different operators (62 total collected cycles) and these data were analyzed using a linear mixed-model statistical analysis. The significance level for this test was set at $p<0.05$.

3.7.2 Three Dimensional Direct Handle Measurements method peak forces analysis

To determine any statistical difference between recordings from different operators, peaks forces data for each sub-task, for each operator were analyzed. In order to determine any statistical difference between different operators, a one-way ANOVA was conducted for each identified sub-task. In total, 39 independent one-way ANOVA were conducted; one per each sub-task. Statistical differences between operators were evaluated with a Tukey's HSD post hoc test. The statistical significance level for each one-way ANOVA was set at $p<0.05$.

3.7.3 STD and 3DDHM method recorded peak forces comparison

To determine any statistical difference between recordings from different methods an independent one-sample T test was employed. The independent one-sample T test was conducted for each sub-task within each of the workstations, and for each of these sub-tasks the peak force as reported by the STD peak force method was compared to the mean of the corresponding sub-task 3DHMM peak force. In total, 39 independent one-sample T-test were conducted; one per each sub-task. The statistical significance level for was set at $p<0.05$.

3.7.4 Three Dimensional Direct Handle Measurements method impulse forces analysis

Two different statistical analyses were performed with impulse forces: determination of any statistical difference between workstations, and determination of any statistical difference between operators on the same workstation. In both cases, one-way ANOVA were conducted. Statistical differences were evaluated with a Tukey's HSD post hoc test. The statistical significance level for each one-way ANOVA was set at $p<0.05$.

4. Results

This chapter presents the results of the data of the current study. The data were recorded on eight different workstations, on 27 different trained operators, in the indicated plants.

4.1 Right and left hands 3DDHM Method recordings comparison

The following chapters reveal the results of the peaks and impulse analyses on the handle-hand location.

4.1.1 Peak Force comparison

This comparison was completed using the resultant peak force for each independent sub-task of WS_7. A linear mixed-model statistical analysis on force peaks of WS_7 revealed that handle-hand location was not statistically significant for any of the sub-task within these workstations (WS_7ST_0: F= 0.009, p= 0.929; WS_7ST_1: F= 1.419, p= 0.300; WS_7ST_2: F=0.572, p= 0.491). The overall means and standard deviations are shown in Table 6.

Sub-Task		Force Peaks [N]		
			LEFT	RIGHT
WS_7ST_0	Push & alignment	AVG	89.32	94.12
		STD	40.80	27.45
WS_7ST_1	Installation	AVG	116.76	102.05
		STD	17.17	21.15
WS_7ST_2	Pull-back	AVG	94.42	105.73
		STD	20.46	14.91

Table 6. The results of the left and right hands' peak forces (mean and standard deviation)

4.1.2 Impulse forces comparison

This comparison was completed using the resultant integrated force-time data for the entire work cycle and each sub-task within WS_7. A linear mixed-model statistical analysis on force impulses of WS_7 revealed that handle-hand location was not statistically significant for this workstation (WS_7: F= 0.599, p= 0.496). In addition, a linear mixed-model statistical analysis on force impulses of WS_7 revealed that handle-hand location was not statistically significant for any of the sub-task within this workstation (WS_7ST_0: F= 1.062, p= 0.361; WS_7ST_1: F= 0.404, p= 0.560; WS_7ST_2: F= 2.585, p= 0.183). The means and standard deviations are shown in Table 7 and 8.

		Force Impulse [Ns]		
			LEFT	RIGHT
WS_7	Whole Cycle	AVG	646.49	564.48
		STD	161.83	99.61

Table 7. The results of the left and right hands' impulse forces on the whole cycle (mean and standard deviation)

Sub-Task		Force Impulse [Ns]		
			LEFT	RIGHT
WS_7ST_0	Push & alignment	AVG	250.84	191.10
		STD	99.90	79.56
WS_7ST_1	Installation	AVG	248.32	290.80
		STD	106.36	82.07
WS_7ST_2	Pull-back	AVG	150.29	85.97
		STD	61.12	28.77

Table 8. The results of the left and right hands' impulse forces sub-task by sub-task (mean and standard deviation)

4.2 Three-Dimensional Direct Handle Measurements method peak forces results workstation by workstation

This section presents resultant peak forces recorded per each workstation in a sub-task by sub-task manner.

4.2.1 Peak forces during battery installation (WS_1)

The mean of peak force per each sub-task and each operator has been calculated and are shown with the correspondent standard deviations in Figure 20***Figure 20***. The following sub-sections provide the results of the statistical analysis.

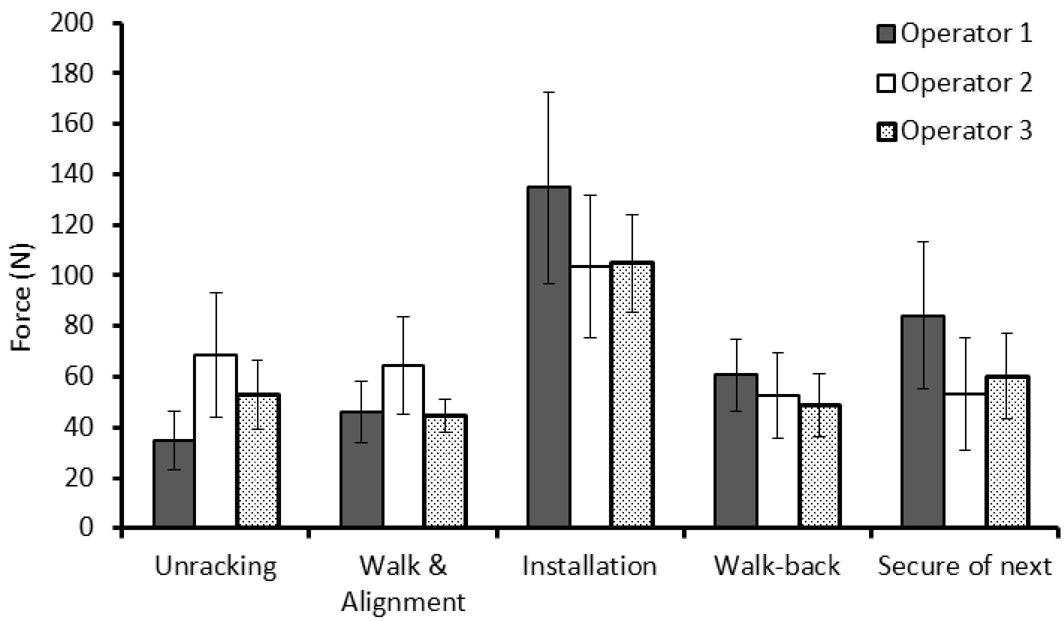

Figure 20. Peak forces recorded per each sub-task per each operator on WS_1 (means and standard deviations are shown).

4.2.1.1 Un-racking (WS_1ST_0)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_1ST_0: $F= 19.48$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP3, and peak forces from OP3 were greater than OP1.

The Y axis, which measures the push/pull efforts, appears to be the dominant axis for all the operators, and a pull effort was clearly the dominant effort provided by the operators. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 9.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	17%	16%	Left Pull	90%	31%	Pull	31%	25%	Lift
2	11%	15%	Left Pull	85%	34%	Pull	1%	51%	Lift
3	6%	22%	Left Pull	90%	33%	Pull	22%	30%	Lift

Table 9. Axis contribution to resultant peak force per each operator for WS_1ST_0 (means, standard deviations, and effort types are shown)

4.2.1.2 *Walk and alignment (WS_1ST_1)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_1ST_1: F= 14.67, $p < 0.001$). However, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP3 and OP1, but no differences were found between OP1 and OP3.

The Z axis, which indicates a lifting effort, appears to be the dominant axis for OP2 and OP3; while OP1 did not use a single axis more than another, and thus their peak force was a combination of all axes. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 10.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	16%	17%	Left Pull	7%	94%	Push	28%	32%	Lift
2	20%	30%	Left Pull	2%	44%	Pull	75%	47%	Lift
3	27%	17%	Left Pull	14%	72%	Push	52%	37%	Lift

Table 10. Axis contribution to resultant peak force per each operator for WS_1ST_1 (means, standard deviations, and effort types are shown)

4.2.1.3 *Installation (WS_1ST_2)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_1ST_2: F= 7.76, p = 0.001). However, the post hoc Tukey HSD revealed that peak forces from OP1 were greater than OP2 and OP3, but no difference where found between OP2 and OP3.

The Y axis, indicating push efforts, appears to be dominant for all the operators. However, for OP1 and OP3 the effort that contributes the most is a push while for OP2 the larger contributor is a pull. Furthermore, a considerable lift effort on (Z axis) is present for all the operators. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 11.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	5%	10%	Left Pull	80%	42%	Push	47%	13%	Lift
2	8%	11%	Left Pull	69%	54%	Pull	33%	45%	Lift
3	15%	13%	Left Pull	48%	82%	Push	30%	17%	Lift

Table 11. Axis contribution to resultant peak force per each operator for WS_1ST_0 (means, standard deviations, and effort types are shown)

4.2.1.4 *Walk-back (WS_1ST_3)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_1ST_3: F= 3.53, p = 0.035). The post hoc Tukey HSD revealed that the peak forces from OP1 were greater than OP3, however no other differences were found.

The Y and Z axes (pull and lift efforts) appear to be the dominant axes for OP2 and OP3; while for OP1, Y axis is dominant with a pull as the main effort. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 12.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	6%	11%	Left Pull	79%	42%	Pull	21%	45%	Lift
2	12%	19%	Left Pull	45%	69%	Pull	54%	32%	Lift
3	32%	22%	Left Pull	54%	56%	Pull	52%	24%	Lift

Table 12. Axis contribution to resultant peak force per each operator for WS_1ST_3 (means, standard deviations, and effort types are shown)

4.2.1.5 Secure of next Battery (WS_1ST_4)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_1ST_4: $F= 10.69$, $p < 0.001$). The post hoc Tukey HSD revealed that the peak forces from OP1 were greater than OP2 and OP3, however no differences were found between OP2 and OP3.

The Y axis (pull effort) appears to be dominant for OP1 and OP2 that most contributes to the resultant peak. However, for OP3, the X and Z axes are the dominant axes with a combined left pull/lift effort. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 13.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	20%	28%	Left Pull	85%	39%	Pull	15%	26%	Lift
2	23%	24%	Left Pull	56%	79%	Pull	16%	35%	Lift
3	51%	26%	Left Pull	8%	57%	Pull	59%	30%	Lift

Table 13. Axis contribution to resultant peak force per each operator for WS_1ST_4 (means, standard deviations, and effort types are shown)

4.2.2 *Peak force during dashboard installation (WS_2)*

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 21. The following sub-sections provide the results of the statistical analysis.

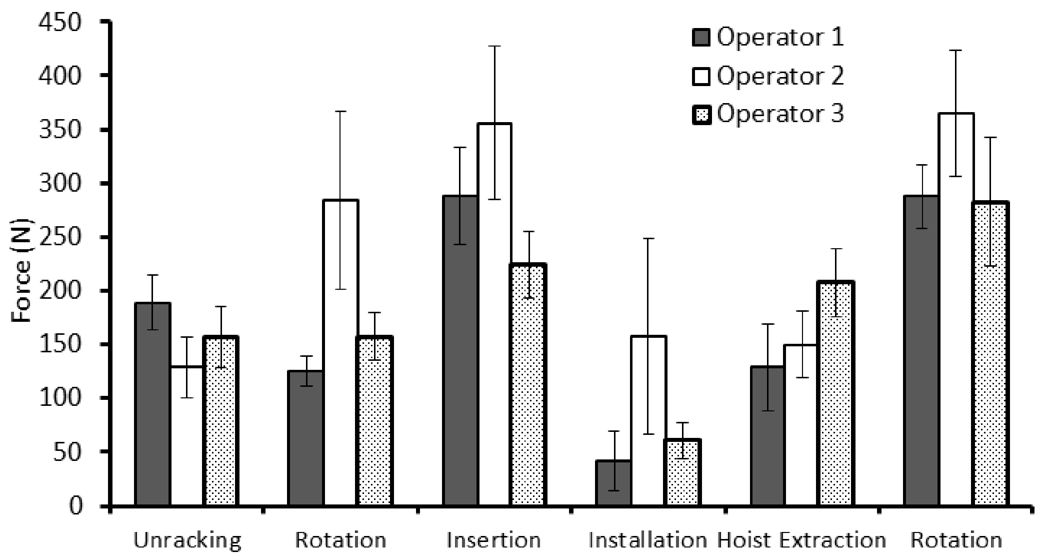

Figure 21. Peak forces recorded per each sub-task per each operator on WS_2 (means and standard deviations are shown).

4.2.2.1 *Un-racking (WS_2ST_0)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_0: $F= 24.65$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP1 were greater than OP3, and peak forces from OP3 were greater than OP2.

The X and Z axes (right pull/lift) appear to be the dominant axes for OP1 and OP3. In contrast, OP2 did not employ a single axis to complete the task, rather used all of axes to produce the peak resultant force. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 14.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	43%	34%	Right Pull	30%	18%	Push	72%	27%	Lift
2	26%	23%	Right Pull	27%	63%	Push	1%	70%	Lift
3	58%	15%	Right Pull	45%	15%	Push	65%	18%	Lift

Table 14. Axis contribution to resultant peak force per each operator for WS_2ST_0 (means, standard deviations, and effort types are shown)

4.2.2.2 Rotation (WS_2ST_1)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_1: F= 58.10, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1 and OP3, but no differences were found between OP1 and OP3.

The X axis (left pull effort) appears to be the dominant axis for all the operators. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 15.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	84%	21%	Left Pull	42%	13%	Pull	33%	12%	Lower
2	86%	11%	Left Pull	36%	11%	Pull	34%	7%	Lower
3	81%	14%	Left Pull	37%	9%	Pull	45%	11%	Lower

Table 15. Axis contribution to resultant peak force per each operator for WS_2ST_1 (means, standard deviations, and effort types are shown)

4.2.2.3 Insertion (WS_2ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_2: F= 36.36, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1, and peak forces from OP1 were greater than OP3.

The Y and Z axes (combined push and lift efforts) appear to be the dominant axes for all the operators. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 16.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	18%	13%	Right Pull	70%	14%	Push	67%	20%	Lift
2	5%	27%	Left Pull	82%	26%	Push	39%	29%	Lift
3	2%	22%	Right Pull	73%	41%	Push	48%	34%	Lift

Table 16. Axis contribution to resultant peak force per each operator for WS_2ST_2 (means, standard deviations, and effort types are shown)

4.2.2.4 Installation (WS_2ST_3)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_3: $F= 27.55$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1 and OP3, but no differences were found between OP1 and OP3.

For OP3, the X axis (left pull) appears to be the dominant axis while, OP1 and OP2 did not employ a single axis to complete the task, rather used all of them to produce the peak resultant force. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 17.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	32%	49%	Left Pull	18%	71%	Push	7%	70%	Lift
2	12%	44%	Left Pull	38%	63%	Push	30%	77%	Lift
3	70%	26%	Left Pull	16%	43%	Push	36%	45%	Lower

Table 17. Axis contribution to resultant peak force per each operator for WS_2ST_3 (means, standard deviations, and effort types are shown)

4.2.2.5 Hoist extraction (WS_2ST_4)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_4: $F= 30.50$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP3 were greater than OP1 and OP2, but no differences were found between OP1 and OP2.

OP1 used mostly the Y axis (pull effort) while, OP2 and OP3 used more of the Z axis (lift effort) to complete this task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 18.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	32%	23%	Left Pull	86%	20%	Pull	24%	25%	Lower
2	8%	56%	Right Pull	9%	62%	Push	42%	46%	Lift
3	9%	22%	Right Pull	35%	47%	Push	59%	54%	Lift

Table 18. Axis contribution to resultant peak force per each operator for WS_2ST_4 (means, standard deviations, and effort types are shown)

4.2.2.6 Rotation (WS_2ST_5)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_2ST_5: $F= 15.65$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1 and OP3, but no differences were found between OP1 and OP3.

All operators did not employ a single axis to complete the task, rather used all of them to produce the peak resultant force. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 19.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	71%	29%	Left Pull	40%	27%	Pull	38%	33%	Lower
2	14%	41%	Left Pull	32%	62%	Push	28%	57%	Lift
3	51%	17%	Left Pull	60%	15%	Pull	60%	14%	Lower

Table 19. Axis contribution to resultant peak force per each operator for WS_2ST_5 (means, standard deviations, and effort types are shown)

4.2.3 *Peak forces during front end module installation - model 1 (WS_3)*

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 22. The following sub-sections provide the results of the statistical analysis.

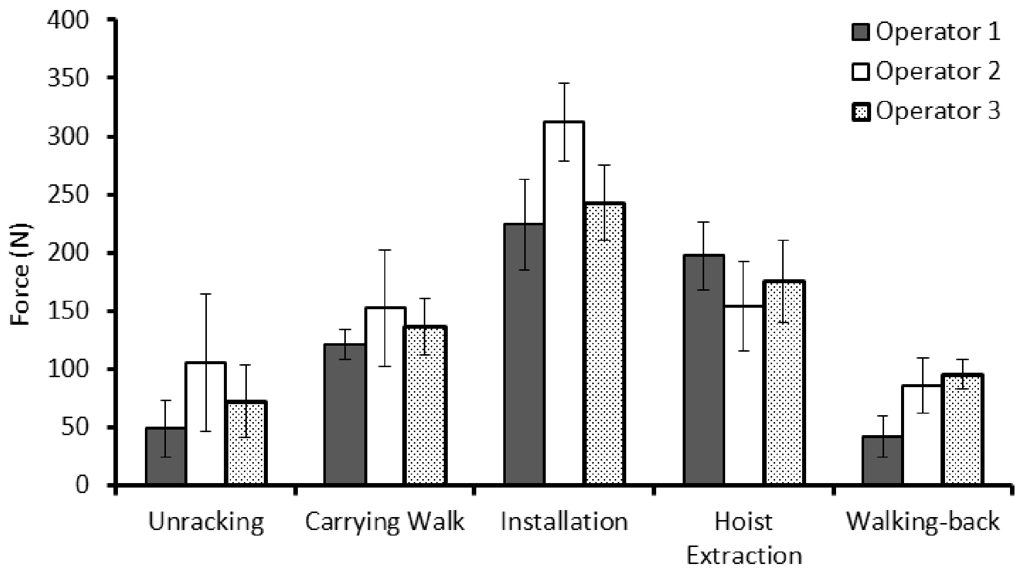

Figure 22. Peak forces recorded per each sub-task per each operator on WS_3 (means and standard deviations are shown).

4.2.3.1 *Un-racking (WS_3ST_0)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_3ST_0: F= 11.01, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1 and OP3, but no differences were found between OP1 and OP3.

OP1 and OP3 did not employ a single axis to complete the task, rather used all of them to produce the peak resultant force, while OP2 used a strategy where most force was produced on the Z axis (lift effort) to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 20.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	30%	35%	Right Pull	28%	65%	Push	5%	75%	Lower
2	16%	25%	Right Pull	5%	50%	Push	70%	71%	Lift
3	11%	16%	Right Pull	22%	51%	Push	27%	90%	Lift

Table 20. Axis contribution to resultant peak force per each operator for WS_3ST_0 (means, standard deviations, and effort types are shown)

4.2.3.2 Carrying walk (WS_3ST_1)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_3ST_1: F= 5.07, p = 0.009). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1, but no other differences were found.

OP1 and OP3 did not employ a single axis to complete the task, rather used all of them to produce the peak resultant force. Conversely, OP2 employed force recorded on the Z axis (lift effort) to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 21.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	13%	27%	Right Pull	2%	60%	Push	28%	72%	Lift
2	18%	15%	Right Pull	4%	45%	Push	79%	48%	Lift
3	17%	23%	Right Pull	16%	66%	Pull	13%	72%	Lift

Table 21. Axis contribution to resultant peak force per each operator for WS_3ST_1 (means, standard deviations, and effort types are shown)

4.2.3.3 Installation (WS_3ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_3ST_2: F= 37.77, p < 0.001). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP1 and OP3, but no differences were found between OP1 and OP3.

All operators produced forces on the Y axis (push effort) to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 22.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	10%	10%	Left Pull	91%	16%	Push	39%	9%	Lift
2	2%	8%	Right Pull	98%	11%	Push	18%	7%	Lift
3	25%	6%	Left Pull	93%	12%	Push	24%	14%	Lift

Table 22. Axis contribution to resultant peak force per each operator for WS_3ST_2 (means, standard deviations, and effort types are shown)

4.2.3.4 Hoist Extraction (WS_3ST_3)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_3ST_3: $F= 11.01$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP1 were greater than OP2, but no other differences were found.

While all operators mostly produced forces on the Y axis (pull effort), it must be noted that they also produced a large portion on the Z axis (lower effort) to complete the task. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 23.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	18%	4%	Right Pull	84%	12%	Pull	51%	9%	Lower
2	26%	10%	Right Pull	79%	21%	Pull	54%	18%	Lower
3	23%	6%	Right Pull	86%	18%	Pull	43%	18%	Lower

Table 23. Axis contribution to resultant peak force per each operator for WS_3ST_3 (means, standard deviations, and effort types are shown)

4.2.3.5 Walking back (WS_3ST_4)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_3ST_4: $F = 48.62$, $p < 0.001$). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 and OP3 were greater than OP1, but no differences were found between OP2 and OP3.

For OP1 and OP2, the Y axis (push effort) appears to be the dominant axis used. However, for OP3 the Y and Z axes were the dominant axes used indicating a combined push-lift effort. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 24.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	22%	37%	Right Pull	47%	35%	Push	28%	86%	Lift
2	38%	46%	Right Pull	52%	56%	Push	20%	37%	Lift
3	2%	20%	Right Pull	34%	55%	Push	68%	35%	Lift

Table 24. Axis contribution to resultant peak force per each operator for WS_3ST_3 (means, standard deviations, and effort types are shown)

4.2.4 Peak forces during front end module installation – model 2 (WS_4)

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 23. The following sub-sections provide the results of the statistical analysis.

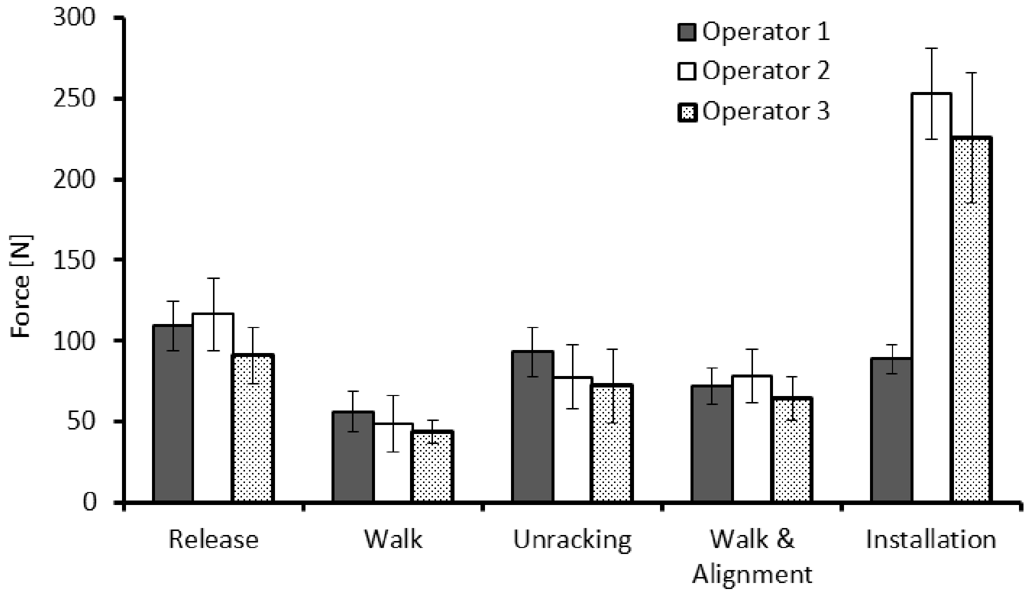

Figure 23. Peak forces recorded per each sub-task per each operator on WS_4 (means and standard deviations are shown).

4.2.4.1 Component release (WS_4ST_0)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_4ST_0: F= 8.140, p = 0.001). Specifically, the post hoc Tukey HSD revealed that peak forces from OP2 were greater than OP3, but no other differences were found.

The Y axis appears to be the dominant axis for all the operators which indicated that a pull effort strategy. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 25.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	11%	10%	Right Pull	96%	14%	Pull	22%	11%	Lift
2	33%	15%	Right Pull	85%	22%	Pull	32%	17%	Lift
3	24%	44%	Right Pull	87%	19%	Pull	5%	16%	Lower

Table 25. Axis contribution to resultant peak force per each operator for WS_4ST_0 (means, standard deviations, and effort types are shown)

4.2.4.2 Walk (WS_4ST_1)

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_4ST_1: F= 2.47, p = 0.096). Additionally, the post hoc Tukey HSD did not find any differences between operators.

For OP1, the Z axis (lift effort) shows to be the predominant axis used. Conversely, OP2 used a left pull effort (X axis) as it contributed most to the resultant peak. Finally, for OP3 it was not possible to identify a dominant axis, therefore a dominant direction effort. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 26.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	26%	32%	Left Pull	37%	50%	Pull	58%	48%	Lift
2	67%	32%	Left Pull	11%	43%	Pull	39%	50%	Lift
3	36%	33%	Left Pull	35%	53%	Pull	21%	65%	Lift

Table 26. Axis contribution to resultant peak force per each operator for WS_4ST_1 (means, standard deviations, and effort types are shown)

4.2.4.3 Un-racking (WS_4ST_2)

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_4ST_2: F= 2.96, p = 0.062). However, the post hoc Tukey HSD test revealed that peak forces from OP1 were greater than OP3, but no other differences were found.

For OP1 and OP3, the Z axis was primarily used, indicating a lowering effort. However, for OP2, it was not possible to identify a dominant axis. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 27.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	22%	29%	Left Pull	48%	66%	Push	46%	30%	Lower
2	17%	57%	Left Pull	19%	56%	Pull	38%	50%	Lower
3	37%	19%	Left Pull	6%	85%	Pull	42%	25%	Lower

Table 27. Axis contribution to resultant peak force per each operator for WS_4ST_2 (means, standard deviations, and effort types are shown)

4.2.4.4 *Walk and alignment (WS_4ST_3)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_4ST_3: $F= 4.53$, $p = 0.017$). However, the post hoc Tukey HSD test revealed that peak forces from OP2 were greater than OP3, but no other differences were found.

The Y axis appears to be dominant for OP1 indicating a pull effort. Conversely, for OP2 and OP3 was not possible to identify a dominant axis. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 28.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	4%	40%	Left Pull	66%	22%	Pull	54%	35%	Lower
2	13%	31%	Right Pull	16%	90%	Push	31%	48%	Lower
3	36%	49%	Right Pull	32%	63%	Push	23%	41%	Lower

Table 28. Axis contribution to resultant peak force per each operator for WS_4ST_3 (means, standard deviations, and effort types are shown)

4.2.4.5 *Installation (WS_4ST_4)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_4ST_4: $F= 76.5$, $p < 0.001$). However, the post hoc Tukey HSD test revealed that peak forces from both OP2 and OP3 were greater than OP1, but no other differences were found between OP2 and OP3.

The Y axis appears to be the dominant axis for OP2 and OP3 indicating a push effort. On the other hand, for OP1, the X axis was the dominant axis indicating a right pull effort as the main contributor. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 29.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	74%	12%	Right Pull	3%	44%	Push	45%	30%	Lower
2	32%	9%	Right Pull	83%	34%	Push	32%	23%	Lift
3	31%	10%	Right Pull	88%	16%	Push	34%	7%	Lift

Table 29. Axis contribution to resultant peak force per each operator for WS_4ST_4 (means, standard deviations, and effort types are shown)

4.2.5 *Peak forces during front Cradle positioning (WS_5)*

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 24. The following sub-sections provide the results of the statistical analysis.

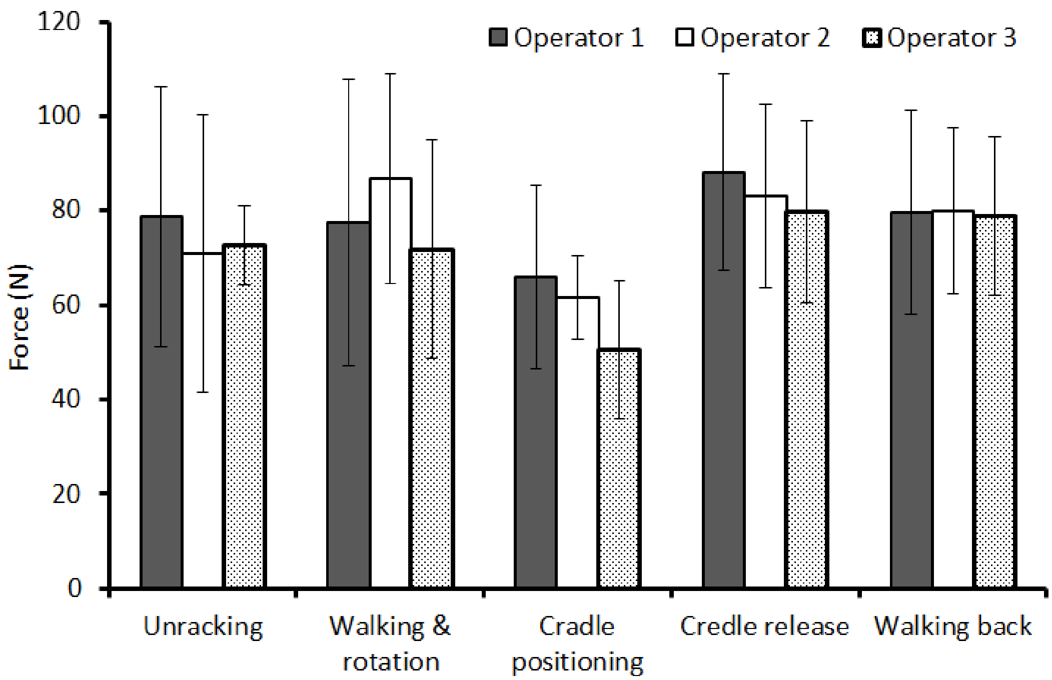

Figure 24. Peak forces recorded per each sub-task per each operator on WS_5 (means and standard deviations are shown).

4.2.5.1 *Un-racking (WS_5ST_0)*

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_5ST_0: $F = 0.504$, $p = 0.607$). Additionally, the post hoc Tukey HSD did not find any differences between operators.

The Y and Z axes appear to be the dominant axes for all the operators and therefore, a combined lift-pull effort was used to complete this task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 30.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	4%	12%	Left Pull	86%	37%	Pull	44%	25%	Lift
2	24%	22%	Left Pull	77%	36%	Pull	50%	32%	Lift
3	26%	9%	Left Pull	69%	22%	Pull	63%	11%	Lift

Table 30. Axis contribution to resultant peak force per each operator for WS_5ST_0 (means, standard deviations, and effort types are shown)

4.2.5.2 Walking and rotation (WS_5ST_1)

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_5ST_1: F = 0.853, p = 0.433). Additionally, the post hoc Tukey HSD did not find any differences between operators.

For OP2 and OP3, the Y and Z axes are the dominant axes indicating a lift-pull effort strategy to complete the task. Conversely, OP1 utilized a lift effort as indicated by a large contribution from the Z axis. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 31.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	20%	19%	Left Pull	3%	92%	Push	39%	31%	Lift
2	38%	24%	Left Pull	51%	34%	Pull	68%	21%	Lift
3	20%	19%	Left Pull	67%	49%	Pull	56%	18%	Lift

Table 31. Axis contribution to resultant peak force per each operator for WS_5ST_1 (means, standard deviations, and effort types are shown)

4.2.5.3 Cradle positioning (WS_5ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_5ST_2: F= 4.11, p = 0.023). However, the post hoc Tukey HSD did not find any differences between operators.

It is not possible to identify a dominant axis for any of the operators as they used a relatively equal combination of all three axes. Mean and standard deviation of each axis contribution to the resultant force are shown in Table 32.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	14%	27%	Left Pull	9%	88%	Pull	20%	49%	Lower
2	6%	16%	Left Pull	33%	88%	Pull	25%	45%	Lift
3	24%	18%	Left Pull	11%	97%	Push	12%	37%	Lift

Table 32. Axis contribution to resultant peak force per each operator for WS_5ST_2 (means, standard deviations, and effort types are shown)

4.2.5.4 Cradle release (WS_5ST_3)

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_5ST_3: F= 0.866, p = 0.428). Additionally, the post hoc Tukey HSD did not find any differences between operators.

The Y axis shows that it was the dominant axis for all the operators indicating that all used a pull effort to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 33.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	4%	10%	Right Pull	82%	20%	Pull	40%	42%	Lift
2	13%	9%	Left Pull	85%	20%	Pull	49%	17%	Lift
3	12%	15%	Left Pull	86%	28%	Pull	23%	40%	Lift

Table 33. Axis contribution to resultant peak force per each operator for WS_5ST_3 (means, standard deviations, and effort types are shown)

4.2.5.5 Walking back (WS_5ST_4)

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_5ST_4: F= 0.010, p = 0.991). Additionally, the post hoc Tukey HSD did not find any differences between operators.

The Y and Z axes show to be the dominant axes for all the operators, indicating a combined lift-pull effort to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 34.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	2%	14%	Right Pull	85%	45%	Pull	35%	19%	Lift
2	10%	12%	Left Pull	75%	56%	Pull	44%	11%	Lift
3	5%	10%	Left Pull	81%	47%	Pull	31%	27%	Lift

Table 34. Axis contribution to resultant peak force per each operator for WS_5ST_4 (means, standard deviations, and effort types are shown)

4.2.6 Peak forces during hard top loading on AGC (WS_6)

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 25. The following sub-sections provide the results of the statistical analysis.

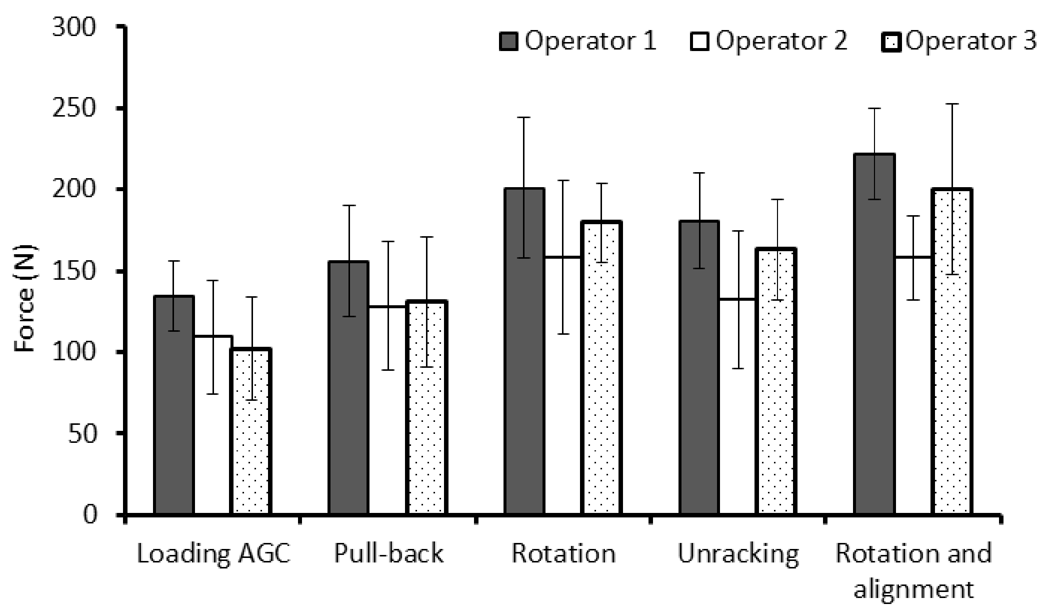

Figure 25. Peak forces recorded per each sub-task per each operator on WS_5 (means and standard deviations are shown).

4.2.6.1 *Loading AGC (WS_6ST_0)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_6ST_0: $F= 4.603$, $p = 0.016$). However, the post hoc Tukey HSD test revealed that peak forces from OP1 were greater than OP3, but no other differences were found.

It was not possible to identify a dominant axis for any of the operators, as they used a relatively equal combination of all three axes. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 35.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	15%	41%	Right Pull	28%	70%	Push	39%	41%	Lift
2	1%	42%	Right Pull	20%	87%	Push	43%	33%	Lift
3	1%	57%	Left Pull	27%	71%	Push	38%	32%	Lift

Table 35. Axis contribution to resultant peak force per each operator for WS_6ST_0 (means, standard deviations, and effort types are shown)

4.2.6.2 *Pull-back (WS_6ST_1)*

A one-way ANOVA revealed that a statistical significant difference does not exist between peak forces from different operators (WS_6ST_1: $F= 2.24$, $p = 0.101$). Furthermore, the post hoc Tukey HSD test revealed that no differences were found between operators.

It was not possible to identify a dominant axis for any of the operators, as they used a relatively equal combination of all three axes. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 36.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	17%	54%	Left Pull	22%	81%	Pull	8%	29%	Lift
2	7%	50%	Left Pull	15%	83%	Push	27%	41%	Lift
3	49%	53%	Left Pull	40%	62%	Pull	12%	25%	Lift

Table 36. Axis contribution to resultant peak force per each operator for WS_6ST_1 (means, standard deviations, and effort types are shown)

4.2.6.3 Rotation (WS_6ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_6ST_2: F= 4.22, p = 0.022). However, the post hoc Tukey HSD test revealed that peak forces from OP1 were greater than OP2, but no other differences were found.

It was not possible to identify a dominant axis for any of the operators, as they used a relatively equal combination of all three axes. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 37.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	25%	56%	Left Pull	30%	72%	Pull	5%	36%	Lift
2	12%	57%	Left Pull	19%	76%	Push	12%	43%	Lift
3	3%	63%	Right Pull	26%	70%	Push	37%	20%	Lift

Table 37. Axis contribution to resultant peak force per each operator for WS_6ST_2 (means, standard deviations, and effort types are shown)

4.2.6.4 Un-racking (WS_6ST_3)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_6ST_3: F= 7.45, p = 0.002). However, the post hoc Tukey HSD test revealed that peak forces from OP1 were greater than OP2, but no other differences were found.

It was not possible to identify a dominant axis for any of the operators, as they used a relatively equal combination of all tree axes. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 38.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	33%	45%	Left Pull	46%	72%	Pull	3%	22%	Lift
2	9%	43%	Left Pull	8%	88%	Push	20%	39%	Lift
3	2%	53%	Right Pull	8%	84%	Push	28%	24%	Lift

Table 38. Axis contribution to resultant peak force per each operator for WS_6ST_3 (means, standard deviations, and effort types are shown)

4.2.6.5 Rotation and alignment (WS_6ST_4)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_6ST_4: F= 11.52, $p < 0.001$). However, the post hoc Tukey HSD test revealed that peak forces from OP1 and OP3 were greater than OP2, but no differences were found between OP1 and OP3.

For all the operators, the X axis was the dominant axis indicating a right pull effort contributes to complete the task. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 39.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	68%	48%	Right Pull	32%	49%	Pull	1%	16%	Lift
2	36%	66%	Right Pull	1%	64%	Push	3%	36%	Lower
3	68%	65%	Right Pull	4%	45%	Pull	7%	15%	Lower

Table 39. Axis contribution to resultant peak force per each operator for WS_6ST_4 (means, standard deviations, and effort types are shown)

4.2.7 *Peak forces during spare tire mounting bracket installation (WS_7)*

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 26. The following sub-sections provide the results of the statistical analysis.

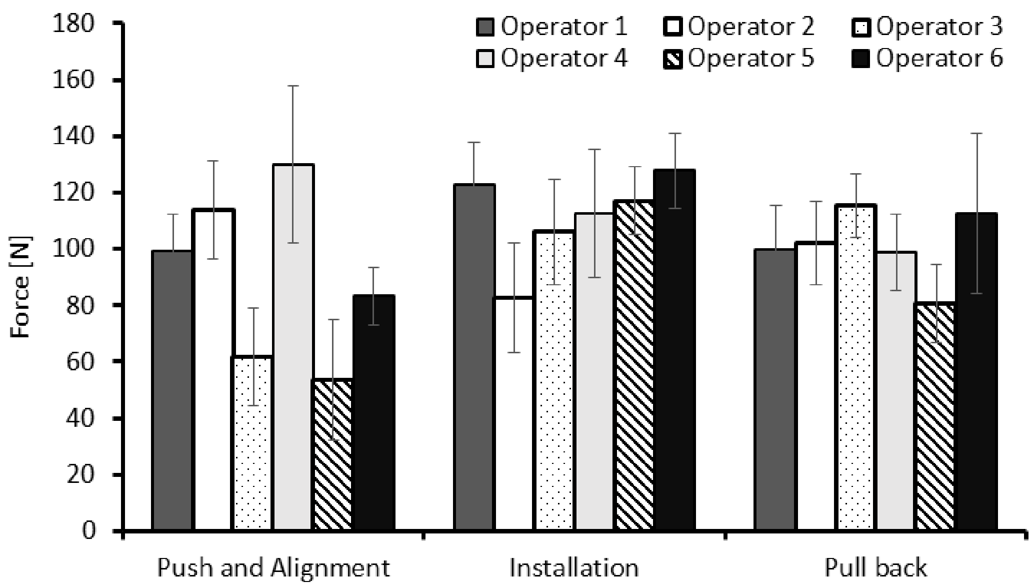

Figure 26. Peak forces recorded per each sub-task per each operator on WS_6 (means and standard deviations are shown).

4.2.7.1 *Push and alignment (WS_7ST_0)*

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_7ST_0: F= 52.17, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP4 were greater than OP1, OP6, OP3 and OP5, but no differences were found between OP4 and OP2. The same test revealed also that peak forces from OP2 were greater than OP6, OP3 and OP5, but no differences were found between OP2 and OP1. Also, peak forces from OP1 were greater than OP3 and OP5, but no differences were found between OP1 and OP6. Finally, peak forces from OP6 were greater than OP3, OP5 and that no differences were found between OP3 and OP5.

It was only possible to identify the Y axis as dominant axis for OP3 and OP4; indicating that a push effort contributes the most to the resultant peak force. However, it was not possible to definitively identify a predominant axis for the other operators. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 40.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	30%	16%	Left Pull	30%	88%	Pull	14%	23%	Lower
2	27%	32%	Left Pull	63%	90%	Pull	17%	41%	Lower
3	6%	25%	Right Pull	80%	46%	Push	34%	24%	Lift
4	39%	20%	Right Pull	54%	33%	Push	27%	63%	Lower
5	6%	47%	Right Pull	11%	61%	Pull	56%	52%	Lower
6	24%	15%	Right Pull	27%	75%	Push	43%	41%	Lift

Table 40. Axis contribution to resultant peak force per each operator for WS_7ST_0 (means, standard deviations, and effort types are shown)

4.2.7.2 Installation (WS_7ST_1)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_7ST_1: F= 16.62, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP1 and OP6 were greater than OP3 and OP2, but no differences were found between OP6, OP1, OP5 and OP4. The same test revealed also that peak forces from OP2 were smaller than all the other operators, while no differences were found between OP3, OP4 and OP5.

It was only possible to identify the axis Y as dominant axis for OP1, OP4, OP5 and OP6; for these operators, a push effort contributes the most to the resultant peak force. Furthermore, for OP4 and OP6, the Z axis (lowering effort) contributes considerably to the peak of the resultant force. On the other hand, the main for OP3 was a lowering effort indicated by the contribution from the axis Z. It was not possible to definitively identify a dominant axis for OP2. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 41.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	30%	16%	Left Pull	30%	88%	Pull	14%	23%	Lower
2	27%	32%	Left Pull	63%	90%	Pull	17%	41%	Lower
3	6%	25%	Right Pull	80%	46%	Push	34%	24%	Lift
4	39%	20%	Right Pull	54%	33%	Push	27%	63%	Lower
5	6%	47%	Right Pull	11%	61%	Pull	56%	52%	Lower
6	24%	15%	Right Pull	27%	75%	Push	-43%	41%	Lift

Table 41. Axis contribution to resultant peak force per each operator for WS_7ST_1 (means, standard deviations, and effort types are shown)

4.2.7.3 Pull-back (WS_7ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between peak forces from different operators (WS_7ST_2: $F= 12.15$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP5 were smaller than all the other operators; no differences were found between OP1, OP4, OP2 and OP6. Peaks from OP3 were greater than OP4 and OP1, but no differences were found between OP3, OP6 and OP2.

The Y axis (pull effort) was the dominant axis for all the operators except for OP2. It is not possible to identify a dominant axis for OP2. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 42.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	37%	16%	Left Pull	78%	44%	Pull	25%	8%	Lift
2	15%	35%	Left Pull	33%	87%	Pull	10%	59%	Lower
3	38%	6%	Left Pull	92%	12%	Pull	5%	3%	Lower
4	6%	7%	Right Pull	93%	17%	Pull	34%	7%	Lower
5	1%	7%	Right Pull	99%	17%	Pull	8%	5%	Lower
6	7%	7%	Left Pull	86%	40%	Pull	28%	27%	Lower

Table 42. Axis contribution to resultant peak force per each operator for WS_7ST_2 (means, standard deviations, and effort types are shown)

4.2.8 Peak forces during windshield installation (WS8)

The mean of peak force per each sub-task and each operator have been calculated and are shown with the correspondent standard deviations in Figure 27. The following sub-sections provide the results of the statistical analysis.

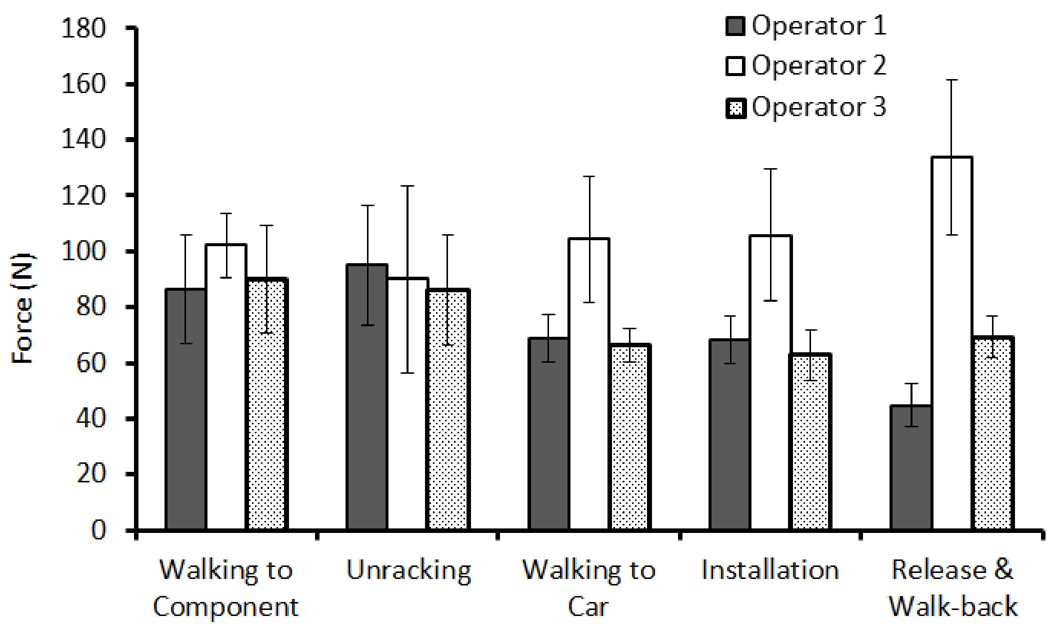

Figure 27. Peak forces recorded per each sub-task per each operator on WS_8 (means and standard deviations are shown).

4.2.7.4 Walking to component (WS_8ST_0)

A one-way ANOVA revealed that a statistical significant difference exists between samples from different operators (WS_8ST_0: F= 4.93, p = 0.011). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP2 were greater than OP1, but no other differences were found.

The Y axis was the dominant axis for OP1 and OP3 indicating that a pull effort contributes the most to the task. However, it was not possible identify a dominant axis for OP2. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 43.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	29%	28%	Left Pull	84%	18%	Pull	36%	15%	Lift
2	15%	22%	Left Pull	7%	83%	Push	24%	48%	Lower
3	30%	9%	Left Pull	70%	19%	Pull	62%	19%	Lift

Table 43. Axis contribution to resultant peak force per each operator for WS_8ST_0 (means, standard deviations, and effort types are shown)

4.2.7.5 Un-racking (WS_8ST_1)

A one-way ANOVA revealed that a statistical significant difference does not exist between samples from different operators (WS_8ST_1: F= 0.566, p = 0.571). Specifically, the post hoc Tukey HSD test revealed that but no differences were found between operators.

The Y axis was the dominant axis used by OP1 and OP3 indicating that a pull effort contributes the most to the resultant peak force. However, it was not possible to determine a dominant axis for OP2. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 44.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	57%	24%	Left Pull	78%	19%	Pull	18%	18%	Lower
2	37%	27%	Left Pull	43%	76%	Pull	3%	45%	Lift
3	33%	35%	Left Pull	74%	45%	Pull	22%	20%	Lift

Table 44. Axis contribution to resultant peak force per each operator for WS_8ST_1 (means, standard deviations, and effort types are shown)

4.2.7.6 Walking to car (WS_8ST_2)

A one-way ANOVA revealed that a statistical significant difference exists between samples from different operators (WS_8ST_2: F= 43.15, p < 0.001). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP2 were greater than OP1 and OP3, while no differences were between OP1 and OP3.

The Y axis (push) appears to be the dominant axis for OP2. In contrast, OP3 did not employ a single axis to complete the task, rather used all of axes to produce the peak resultant force. It is not possible to find a dominant axis for OP1. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 45.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	3%	38%	Right Pull	13%	84%	Push	13%	42%	Lift
2	21%	40%	Left Pull	58%	60%	Push	2%	42%	Lower
3	29%	38%	Right Pull	33%	66%	Push	39%	34%	Lift

Table 45. Axis contribution to resultant peak force per each operator for WS_8ST_2 (means, standard deviations, and effort types are shown)

4.2.7.7 Installation (WS_8ST_3)

A one-way ANOVA revealed that a statistical significant difference exists between samples from different operators (WS_8ST_3: $F= 45.99$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP2 were greater than OP1 and OP3, while no differences were between OP1 and OP3.

The Z axis was shown to be the dominant axis, indicating a lift effort, for OP1 and OP3. Furthermore, a considerable contribution was seen in the Y axis (push effort) for OP1 and OP2. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 46.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	34%	11%	Right Pull	33%	17%	Push	86%	12%	Lift
2	3%	41%	Right Pull	66%	43%	Push	19%	50%	Lift
3	12%	34%	Right Pull	10%	69%	Push	63%	21%	Lift

Table 46. Axis contribution to resultant peak force per each operator for WS_8ST_3 (means, standard deviations, and effort types are shown).

4.2.7.8 *Release and walk-back (WS_8ST_4)*

A one-way ANOVA revealed that a statistical significant difference exists between samples from different operators (WS_8ST_4: $F= 114.59$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that peak forces from OP2 were greater than OP3, and that peak forces from OP3 were greater than peak forces from OP1.

The Y axis (pull effort) was the dominant axis for OP1, while Y (push effort) was dominant for OP2. For OP3, a considerable contribution was provided on the Z and X axes indicating a combined lift-right effort. The mean and standard deviation of each axis contribution to the resultant force are shown in Table 47.

OP	X Axis			Y Axis			Z Axis		
	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT	MEAN	STDEV	EFFORT
1	28%	13%	Left Pull	88%	16%	Pull	25%	27%	Lift
2	23%	12%	Left Pull	68%	51%	Push	46%	29%	Lower
3	57%	35%	Right Pull	23%	44%	Push	55%	14%	Lift

Table 47. Axis contribution to resultant peak force per each operator for WS_8ST_4 (means, standard deviations, and effort types are shown)

4.3 STD and 3DDHM Method recorded peak forces comparison

In this section, peak forces recorded through the two different methods are shown and compared using a statistical analysis.

4.3.1 Battery installation (WS_1)

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 28.

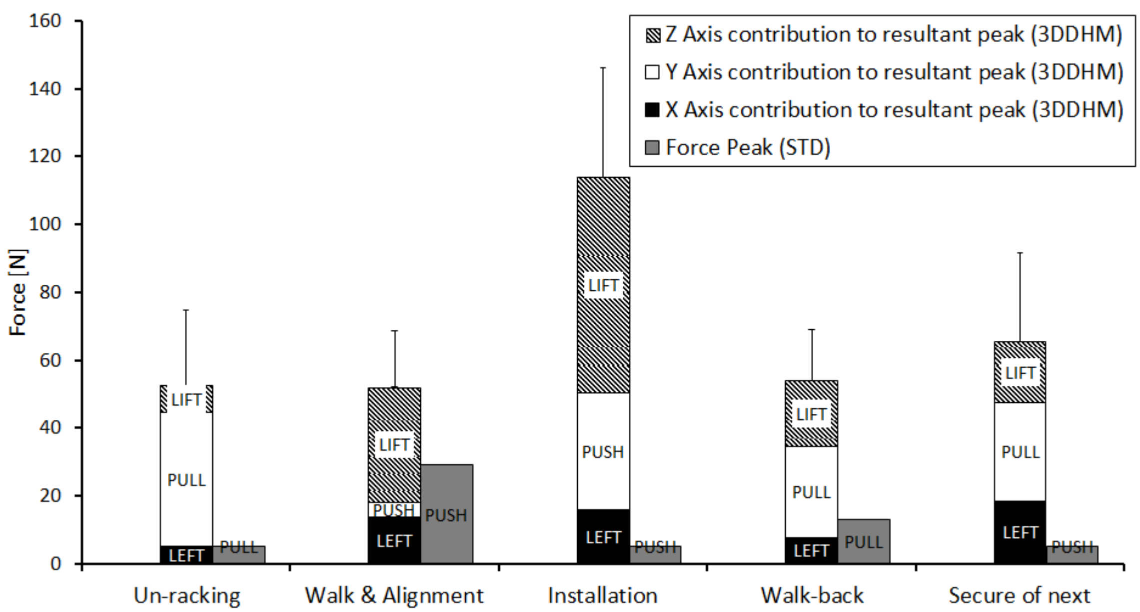

Figure 28. Peaks comparison on WS_1; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_1ST_0: $t = 17.11$, $p < 0.001$; WS_1ST_1: $t = 11.29$, $p < 0.001$; WS_1ST_2: $t = 27.48$, $p < 0.001$; WS_1ST_3: $t = 21.70$, $p < 0.001$; WS_1ST_4: $t = 18.72$, $p < 0.001$).

4.3.2 Dashboard installation (WS_2)

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 29.

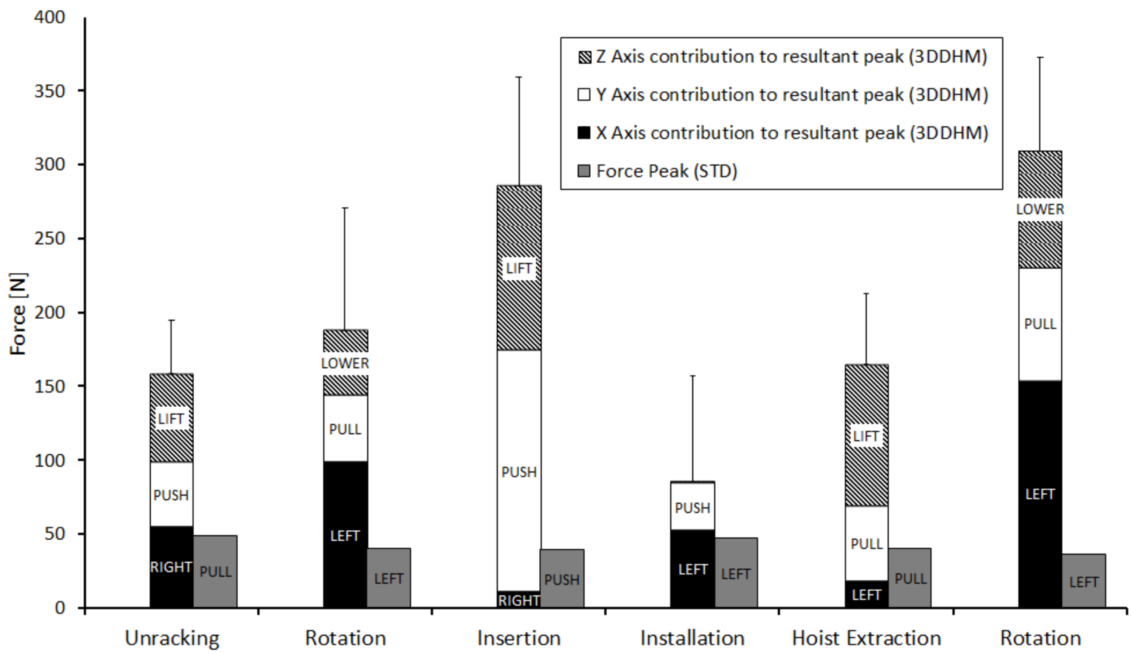

Figure 29. Peaks comparison on WS_2; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_2ST_0: $t = 24.22$, $p < 0.001$; WS_2ST_1: $t = 14.06$, $p < 0.001$; WS_2ST_2: $t = 26.89$, $p < 0.001$; WS_2ST_3: $t = 4.20$, $p < 0.001$; WS_2ST_4: $t = 20.50$, $p < 0.001$; WS_2ST_5: $t = 34.31$, $p < 0.001$).

4.3.3 *Front end module installation – model 1 (WS_3)*

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 30.

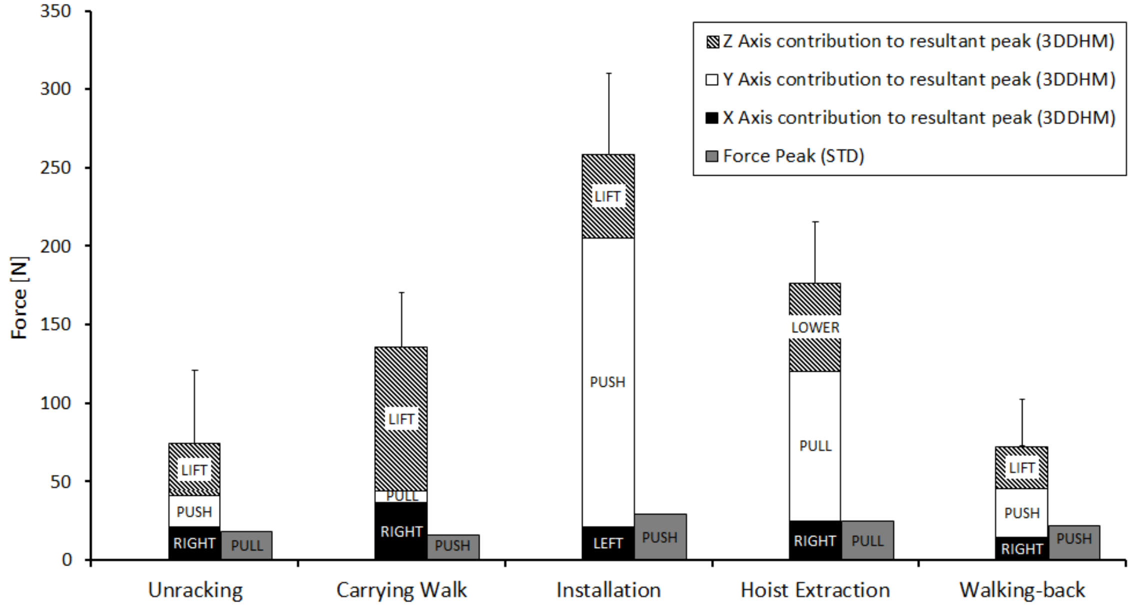

Figure 30. Peaks comparison on WS_3; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_3ST_0: $t = 9.71$, $p < 0.001$; WS_3ST_1: $t = 27.77$, $p < 0.001$; WS_3ST_2: $t = 35.53$, $p < 0.001$; WS_3ST_3: $t = 31.49$, $p < 0.001$; WS_3ST_4: $t = 16.80$, $p < 0.001$).

4.3.4 *Front end module installation – model 2 (WS_4)*

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 31.

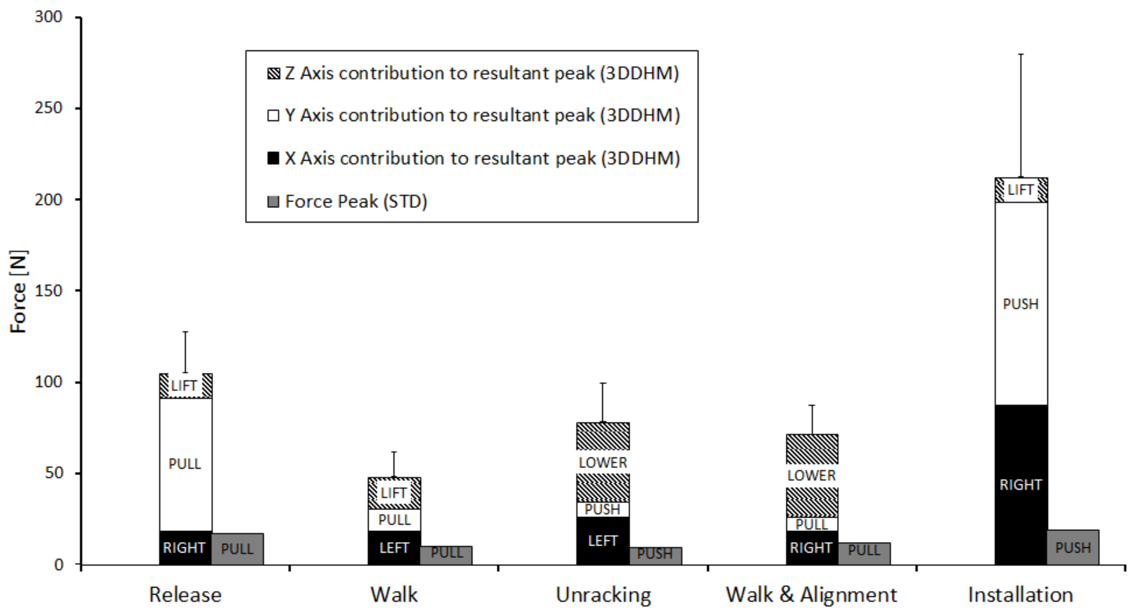

Figure 31. Peaks comparison on WS_4; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_4ST_0: $t = 26.14$, $p < 0.001$; WS_4ST_1: $t = 18.42$, $p < 0.001$; WS_4ST_2: $t = 21.98$, $p < 0.001$; WS_4ST_3: $t = 25.50$, $p < 0.001$; WS_4ST_4: $t = 19.31$, $p < 0.001$).

4.3.5 *Front Cradle installation (WS_5)*

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 32.

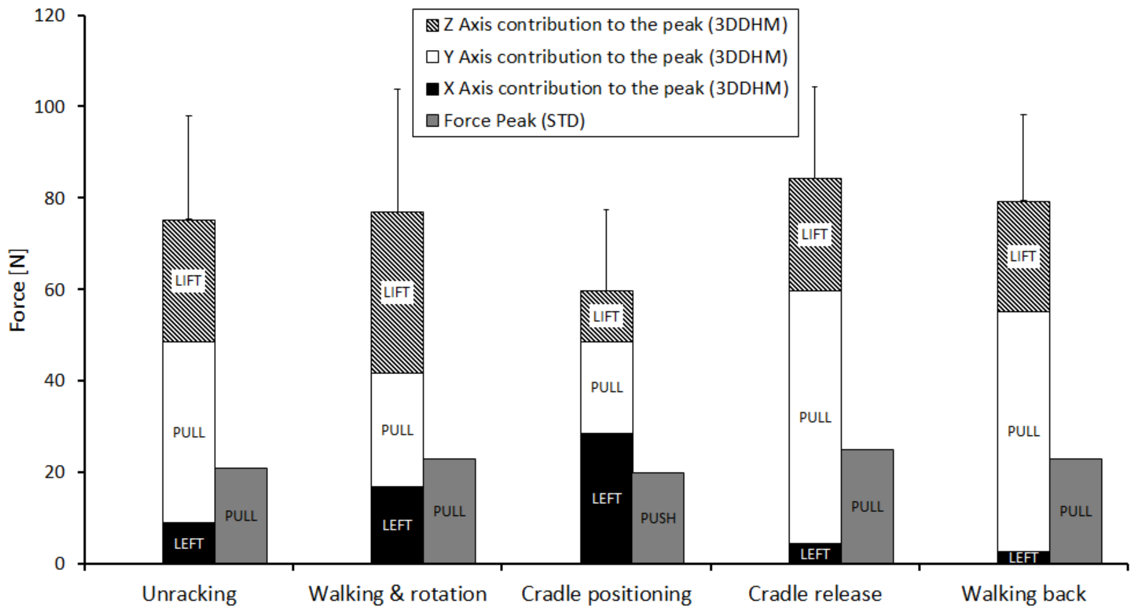

Figure 32. Peaks comparison on WS_5; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_5ST_0: $t = 16.54$, $p < 0.001$; WS_5ST_1: $t = 14.04$, $p < 0.001$; WS_5ST_2: $t = 15.07$, $p < 0.001$; WS_5ST_3: $t = 20.51$, $p < 0.001$; WS_5ST_4: $t = 20.19$, $p < 0.001$).

4.3.6 Hard top loading on AGC (WS_6)

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 33.

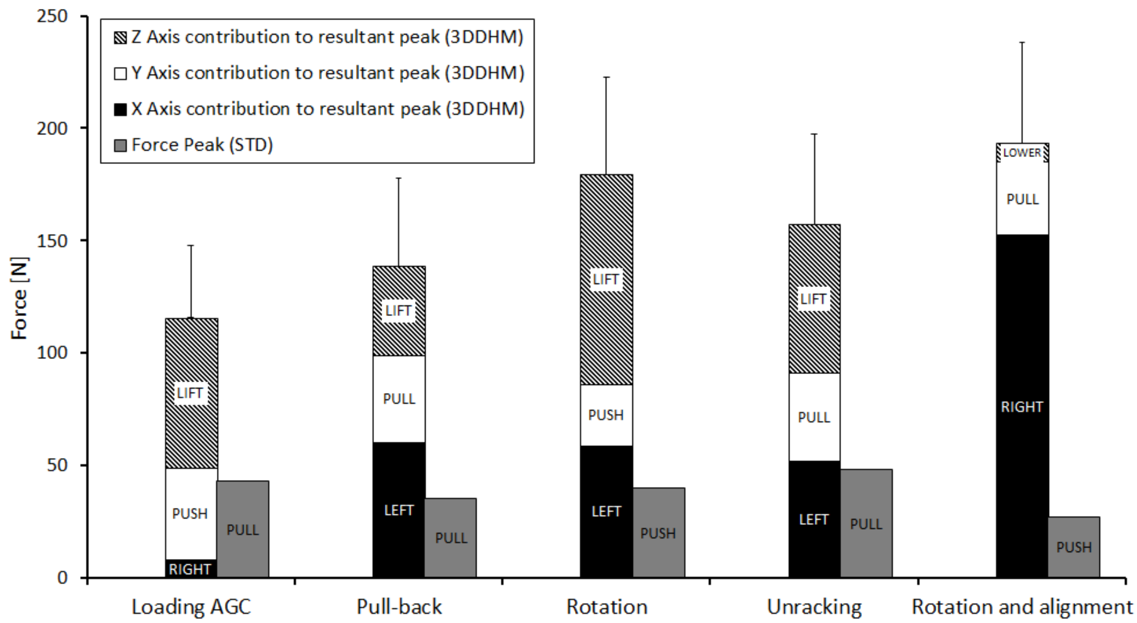

Figure 33. Peaks comparison on WS_6; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_6ST_0: $t = 14.84$, $p < 0.001$; WS_6ST_1: $t = 17.64$, $p < 0.001$; WS_6ST_2: $t = 21.32$, $p < 0.001$; WS_6ST_3: $t = 17.98$, $p < 0.001$; WS_6ST_4: $t = 24.46$, $p < 0.001$).

4.3.7 Spare tire mounting bracket installation (WS_7)

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 34.

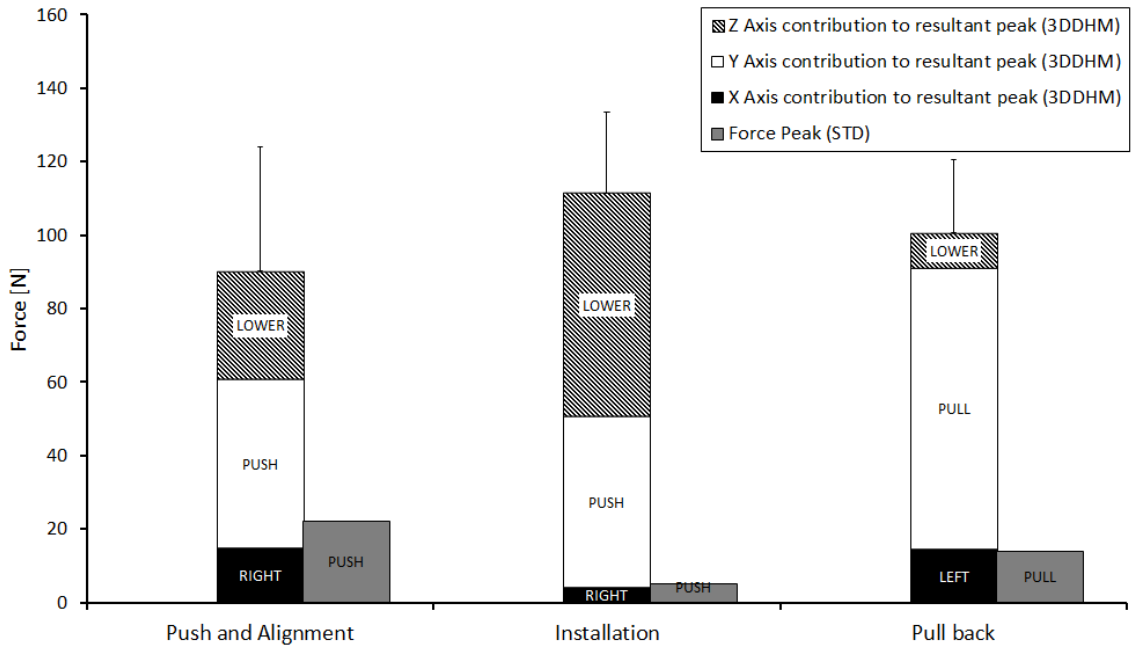

Figure 34. Peaks comparison on WS_7; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_7ST_0: $t = 19.89$, $p < 0.001$; WS_7ST_1: $t = 51.34$, $p < 0.001$; WS_7ST_2: $t = 46.41$, $p < 0.001$).

4.3.8 Windshield Installation (WS_8)

The averages of peaks recorded per each sub-task with the two different methodologies are shown with in Figure 35.

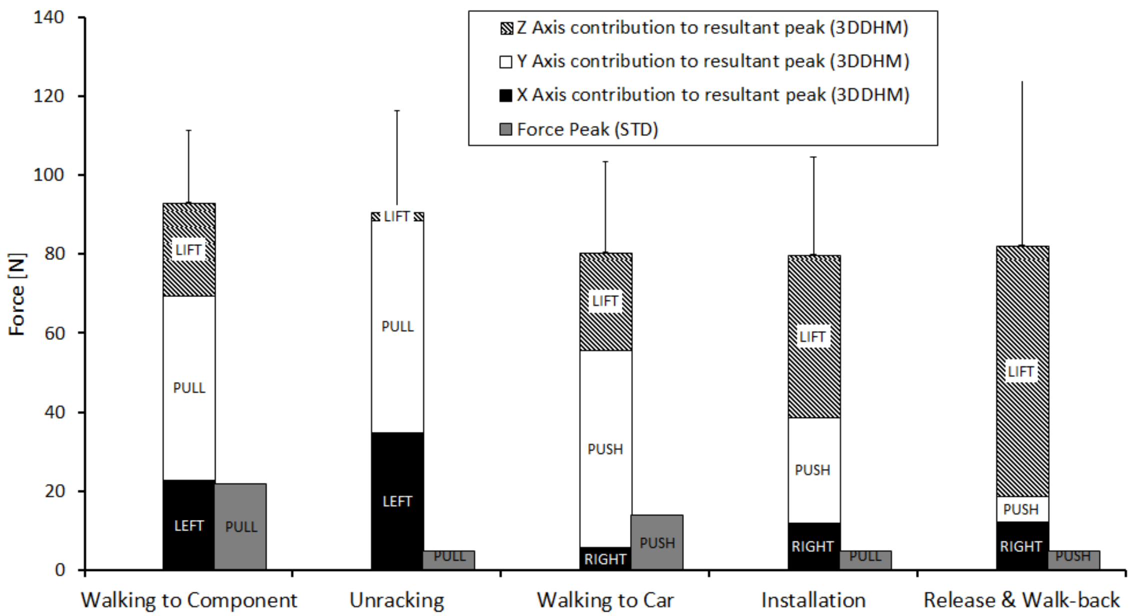

Figure 35. Peaks comparison on WS_8; correspondent standard deviations are shown for peaks recorded with the 3DDHM method.

A one-sample T test demonstrates that, for each sub-task, a statistically significant difference exists between the peak force as measure by the STD method and the 3DHMM method (WS_8ST_0: $t = 30.50$, $p < 0.001$; WS_8ST_1: $t = 25.57$, $p < 0.001$; WS_8ST_2: $t = 22.48$, $p < 0.001$; WS_8ST_3: $t = 23.42$, $p < 0.001$; WS_1ST_4: $t = 14.35$, $p < 0.001$).

4.4 Integrated forces analysis on 3DDHM method collected data

The resultant force integrations of each workstation are shown in Figure 36.

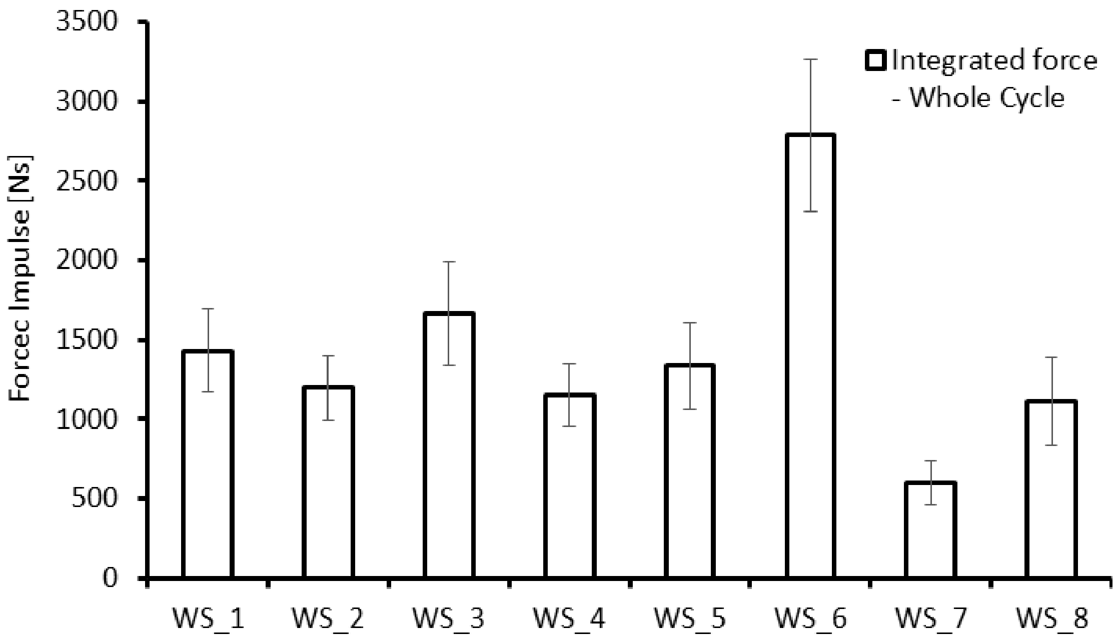

Figure 36. The resultant force integration on the whole cycle per each workstation without any operator discrimination (Means are shown with the correspondent standard deviations)

A one-way ANOVA revealed that a statistical significant difference exists between samples from different workstations ($F = 305.02$, $p < 0.001$). The post hoc Tukey HSD test shows that: force impulse from WS_6 was greater than all the other workstations; force impulse from WS_3 was smaller than WS_6 but greater than all the others; force impulse from WS_1 and WS_5 were smaller than WS_3 and WS_6 but greater than all the others; force impulse from WS_2, WS_4 and WS_8 were greater than WS_7 but smaller than all the others.

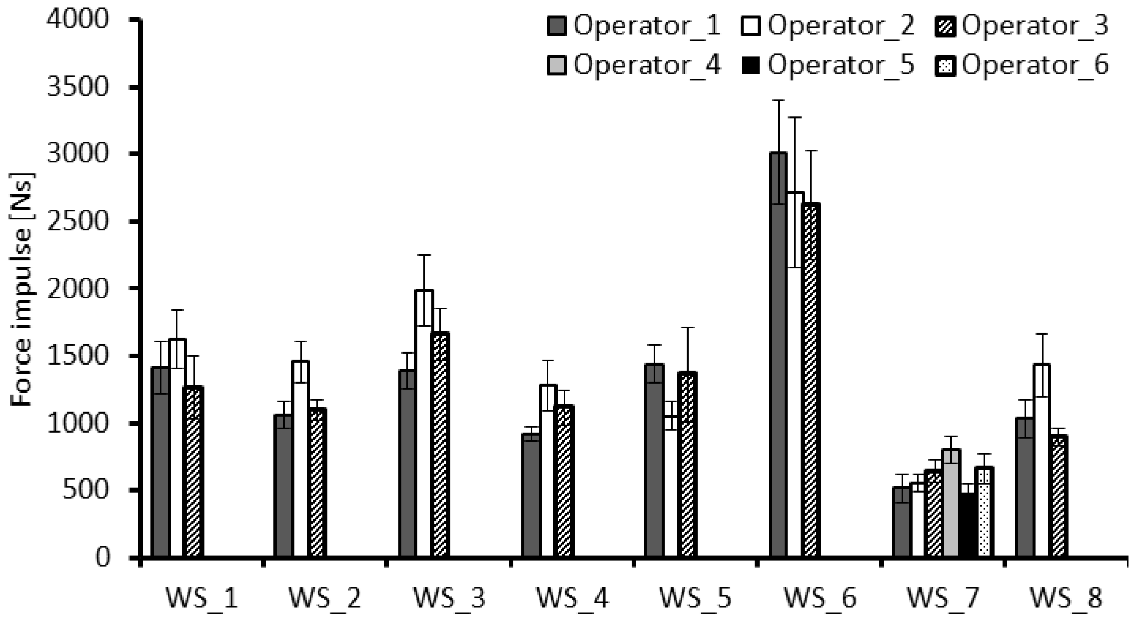

Figure 37. The resultant force integration on the whole cycle per each workstation per each operator (Means are shown with the correspondent standard deviations)

For WS_1, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_1: $F = 15.69$, $p < 0.001$, Figure 37). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP2 was greater than OP1 and OP3, while there were no differences between OP1 and OP3.

For WS_2, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_2: $F = 76.76$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP2 was greater than OP1 and OP3, while there were no differences between OP1 and OP3.

For WS_3, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_3: $F = 50.14$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP2 was greater than OP3, and that force impulse from OP3 was greater than OP1.

For WS_4, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data s from different operators (WS_4: $F = 15.60$, $p < 0.001$).

Specifically, the post hoc Tukey HSD test revealed that force impulse from OP2 was greater than OP3, and that force impulse from OP3 was greater than OP1.

For WS_5, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_5: $F = 7.53$, $p = 0.002$). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP1 and OP3 was greater than OP2, while no differences were found between OP1 and OP3.

For WS_6, a one-way ANOVA revealed that a statistical significant difference does not exist between force impulse data from different operators (WS_6: $F = 2.88$, $p = 0.068$). Furthermore, the post hoc Tukey HSD test confirmed that there were no differences between operators.

For WS_7, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_7: $F = 34.12$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP1 was greater than all the other operators; force impulse from OP3 and OP6 were greater than OP2, OP4 and OP5; no differences were found between OP2, OP4 and OP5, and no differences were found between OP3 and OP6.

For WS_8, a one-way ANOVA revealed that a statistical significant difference exists between force impulse data from different operators (WS_8: $F = 60.54$, $p < 0.001$). Specifically, the post hoc Tukey HSD test revealed that force impulse from OP2 was greater than OP1, and that force impulse from OP1 was greater than OP3.

5. *Discussion*

The current study analyzed two methods to quantify the physical forces required to operate lift-assist devices during automotive assembly, performed by trained assembly operators. A study conducted by Van der Beek et al. (1998) proved that physical forces can be assessed with a proper accuracy only by direct measurement methods at the workplace level. Therefore, it is fundamental to record applied manual forces during normal assembly line operations to achieve an optimal understanding of the magnitude of physical force required to complete their work tasks.

The STD methodology (current standard used by FCA) requires a trained ergonomist to perform force measurements on elements (sub-tasks) of the entire task while normal production is stopped. This method only allows for a limited amount of information to base ergonomic decisions as it only provides single-axis force data and, only reports the peak force obtained for each sub-task. Recording forces only in one-axis can lead to errors in the ergonomic analysis as only aspects of the operator efforts are measured. For instance, if a sub-task requires a combined push/lift effort but the ergonomist only records the force on the pull axis, an incorrect ergonomic evaluation can occur and therefore, risks associated with the task remain.

However, the second method, 3DDHM, attempted to address the limitations of the STD by recording continuous applied forces, of three axes rather than one and, from experienced operators during vehicle assembly operations. Based on the results of this work, significant differences between the two methodologies were shown. The 3DDHM method reported greater resultant peak forces than the STD method. It also provided a more comprehensive set of data, on which different analyses have been conducted. By recording three different operators on each workstation, we captured the importance of the human variability related to preforming the same task, as in most cases peak and impulse forces differed between operations, independent of the workstation. In conclusion, the 3DHMM allowed the researchers to achieve results that cannot be achieved with the STD methodology. Particularly, the 3DDHM methodology allowed for the force demand comparisons of different workstations and between operators all the while recording these forces during normal automotive assembly production.

The comparison of peak forces recorded between both methodologies revealed that the 3DDHM always reported greater forces than those recorded by the STD method. This difference can be attributed to the following two reasons: the 3DDHM allowed for the recording of multi-axes instead of a single axis recording, and the 3DDHM monitored the applied forces during the dynamic task rather than a single static element of the task. Firstly, the STD method required the experienced ergonomist to ensure that the force recording occurred in the direction of intention, known as the Force in Intended Direction (FID), and if this cannot be completed a misrepresentation of the applied force can occur. On the other hand, the 3DDHM method does not require the ergonomist to be concerned with the FID since all the three primary axes are recorded. The forces in all 3 axes allows for the computing of the resultant force, which allows for the identification the peak of the resultant independent of the accuracy of sensor orientation. In this way, all 3 axis contributions to the overall effort are considered, and the ergonomist does not have to identify the FID prior the actual force measurements. In addition, measuring all the forces that the operators are applying provides for a more comprehensive understanding of the physical demands of tasks. From this, the ergonomist can ensure the effort, independent of axes, performed during the job task does not exceed the recommended limits to avoid muscles and joints injuries. As demonstrated by Van der Beek et al. (1998) it is incorrect to assume that push and pull forces are purely horizontal because the resultant force usually has a vertical component that must be considered, and such forces are not recorded with single-axis measurement devices. Moreover, examining the contribution of each primary axis to the resultant is fundamental to determining whether the peak of the resultant is due to a specific single axis effort or to a combination of multiple axes. This information is essential to further analyze the sub-task with the most appropriate ergonomic tool. For example, a sub-task identified as a push would be evaluated with a certain ergonomic tool that is different than the tool that would be used to evaluate a lift effort. In conclusion, once the peak force is recorded, it is important to know the actual effort type to employee the proper ergonomic analyses. This is vital when attempting to limit the risk of injury to workers as specific physical efforts require a very specific set of muscles and joints to produce these specific efforts, in the event of a multi-axis effort, many muscles and joints are used to create such efforts, and if a multi-axis effort is recorded as a single axis effort, the ergonomic assessment is limited in reducing the risk of injury to the worker.

Secondly, the method at which the forces were recorded was different, for the STD a trained ergonomist collected the data while production was stopped, whereas the 3DHMM allowed for the continuous time recording of the applied forces by the trained operator during production. Bao et al., (2009) demonstrated that direct measurements are more sensitive and more accurate rather than ergonomists estimations or simulations. The idea to use an instrumented handle to directly record forces from operators operating a lift-assist is novel to these tasks. However, McGorry et al. (2004) used an instrumented handle to directly measure the physical exertion required to a worker during meat cutting. This research directly measured the forces at the hand-tool interface, and concluded that a direct measurement of forces is vital for accurate ergonomic assessments. This recommendation was taken into considerations for the 3DDHM method, as all forces applied at the hand-handle interface during assembly line operations were recorded continuously throughout the work tasks. This allowed researchers to then determine when the force peak occurred and the magnitude of this peak, and thus, prevents users from missing forceful exertions of the job task that is omitted by the STD methodology. The STD method measures the forces in the FID determined by the ergonomist; a wrong determination of the effort direction can introduce errors in the force measurements. Consequently, an erroneous measurement of the force demand would lead to an incorrect evaluation of the workstation, generating risky situations. For instance, a certain workstation might be considered safe even if it requires the operators to perform efforts beyond the acceptable limits, all due to measurement error.

Resultant peak forces and axes contributions were reported in the current study in order to compare peak forces recorded from different operators and, to examine the contribution of each axis to the peak of the resultant. This allowed for a better understanding of the importance of the operator's strategy employed to perform the workstation sub-task. Applied forces were collected during assembly line operations from actual trained operators who use the lift-assist devices daily. This advantage of the 3DDHM method allowed for direct comparisons between different operators' strategies at the workstation level, rather than data obtained from a single ergonomist. Specifically, the current study revealed statistical differences in different operators' peak forces, and differences in primary axes contribution. Firstly, statistically significant differences between resultant peak forces were recorded from different operators performing the same sub-task. These differences identify the importance of the variability in the strategies that humans employ to complete the same tasks. Specifically, in 31 of the 39 analyzed sub-tasks (79.5%) a statistically significant difference was found between operators. Secondly, this study revealed that the resultant peak force was influenced by different effort types, or combinations of effort types per different operators. Therefore, the process may be different for each operator. Operators often used a combined effort strategy to complete the sub-task, which is not easily captured using the STD method. The 3DDHM method measures the forces and accurately records the effort direction and the effort magnitude. This prevents errors in the measurement of the force demand. Thus, the 3DDHM provides a wider set of information than the STD method, allowing a more accurate ergonomic evaluation of the targeted workstation. Furthermore, the ability to measure from multiple operators allows ergonomists to understand which technique required the least amount of operator force efforts, possibly allowing for an indication of the optimal strategy. Once these strategies are identified, a well-targeted training program could be arranged to show all the operators the most ergonomically effective strategy.

It is important to note that the 3DDHM methodology required the instrumented handle to be secured on one handle location of the involved lift-assist device to record the physical forces applied by the operators. The study design was such that the 3DDHM was placed on the right-handle of the assist, as it was assumed that operators would apply forces on the handles in a symmetrical manner. To test this theory, we investigated whether the operators applied different forces in each hand for the same given task, and we tested this by recording the hand forces from both the left and right hands' during operation on one workstation (WS_7). The results of this comparison showed that the peak forces applied by the left and right hands on this workstation did not significantly differ, therefore proving that operators applied forces in a symmetrical manner. From this, applied forces were assumed to be symmetrical on all workstations that were collected. This allowed researches to measure forces only on one hand.

The 3DDHM methodology has the significant advantage of performing a time-continuous recording of forces, which provides the ability to calculate the integral of the force-time data. The current study utilized this ability by calculating the integral of the resultant force-time data for each operator's cycle, for each workstation. This technique allowed us to investigate the cumulative force effort by each operator, while also allowing us to compare the required cumulative force between each workstation. Thus, rather than perform an analysis on a single sub-task within a workstation cycle, the overall physical demand of a certain workstation could be understood. Doing so, different workstations comparison is now possible. The importance of understanding the time history of force exertion (effort) cannot be understated given that this allows users to not only consider the peak force exerted, but also the time that each effort is sustained. Apart from the intensity of the exerted forces, frequency and duration of the exposure deeply influence the physical demand and therefore, an integrated exposure measurement is suggested (Van der Beek et al., 1998). When employing the STD methodology, the peaks for each sub-task are measured during a simulation of assembly operations; subsequently, an ergonomics analysis on those peaks is performed sub-task by sub-task. In this way, peak forces sustained for one second or for ten seconds would lead to identical results. An approach that uses only a single time-point of effort data does not lend to fully understanding injury mechanics associated with joint loading and muscle fatigue. Since work-related tasks require forces to be applied for some amount of time, even if minimal, the forces should be considered when performing an ergonomics analysis to ensure a comprehensive workstation evaluation. Furthermore, since this innovative impulse force analysis produces a single value that represents the total required effort per each workstation, it is possible to compare workstations, given that workstations vary in the sub-tasks required. The current study revealed that impulse force computed on WS_6 was more than four times greater than the impulse force computed on WS_7. At the same time, WS_6 impulse force was approximately double the impulse forces from WS_1, WS_2, WS_4, WS_5, and WS_8. This technique has the potential to aid in identify full workstation design ergonomics issues. For example, the magnitude of force impulse on WS_6 may indicate a need for a more in-depth ergonomics analysis. Specifically, WS_6 was identified as the most physically demanding workstation. These finding may be explained by the fact that the lift-assist device appeared to be excessively heavy and the operators appeared to sustain the forceful exertion for long amount of time to move in the desired direction. However, currently there is no single ergonomics capability limit to that will allow for a simple evaluation of the force impulse values indicating the risk level of work-related injuries.

Finally, the impulse method provides the ability to compare between operators working on the same workstation. This analysis strengthened what has already been proven by the peaks analysis: force exertion varies between operators for the same given task. At this point it is reasonable to conclude that the various strategies employed by the operators, as already proven, are responsible for differences in the overall total effort. Therefore, the impulse force analysis could be performed to seek the best strategy and thereafter, use this information for future training programs or, design recommendations.

In this study, some limitations and assumptions were made regarding the hand-handle location, the handle orientation, and the operators, all of which deserve discussion.

Firstly, forces from all but one workstation were recorded using from the right handle. However, we have proven for WS_7 that the operators performed the task using symmetrical forces. Based on these results, we assumed this to be true for all the investigated workstations. In order to overcome this limitation, two instrumented handles connected to the same recording system would be able to contemporaneously measure forces on both hands.

Secondly, most of the lift-assists targeted in the current study were roof-chained. (WS_1, WS_3, WS_4, WS_5, and WS_8). This means that they could swing a few degrees while operated. However, the axis reference system of the sensor in the handle is static and consistent with the neutral position of the device. A change in the inclination of the device would generate a change in the orientation of the axis reference system. Unfortunately, the handle device is not equipment with an instrument to measure kinematic changes during operation. This limitation could have caused measurement error with our understanding of individual axis contribution. However, by calculating the resultant we determined the overall scalar portion of force that each operator produced accurately.

Thirdly, the current study has revealed a great variability in the data recorded for different operators. These differences have been related to the different strategies employed by the operators. However, it was only possible to capture the kinetics of the job tasks (i.e. exerted forces); it was not possible to record the kinematics (i.e. movements performed) of each operator while performing the job task. To record the kinematics, a motion capture system would aid the 3DHMM in understanding how and why operators vary in their exertion force during this task.

Lastly, for the current study, it was neither possible to obtain any anthropometric information such as height and weight, nor to note gender and age of the operators, due to the privacy policies associated with the unionized environment. At the same time, it was not possible to obtain any information about the operators' years of experience.

5.1 Hypothesis Revisited

1) *The calculated difference between the measured peak forces independent of task type will result in statistical significant differences.*

The STD and 3DDHM peak forces comparison showed statistically significant differences between the forces recorded by the two methodologies; the current study revealed that the 3DDHM method recorded greater peak forces rather than the STD method, independently from the analyzed sub-task, and therefore the results support that the null hypothesis was rejected, accepting this hypothesis. The expected differences were proven, and they were related to two aspects. Firstly, since forces are three-dimensional in nature, a precise measurement can be achieved only through a multi-axis measurement method (Korkmaz et al, 2013); the 3DDHM method achieved to measure force on the three primary axes. Secondly, Koppelaar and Wells (2005) concluded that direct on-field measurement methods are the most reliable. The 3DDHM method recorded forces during real assembly operations whereas the STD method recorded forces during a simulation of the job-task while normal production is not occurring. For the above-mentioned reasons, the current study concluded that the 3DDHM methodology achieved more valid results.

2) The integrated forces analysis will show, with statistically significance, a difference in the physical demand will exist between different workstations.

The impulse force analyses revealed statically significant difference in impulse magnitudes between workstations and thus, the null hypothesis is rejected, accepting this hypothesis. Each workstation is designed according to mass, dimensions and shape of the part to be moved around and/or installed on the vehicle. Since the recorded workstations were differently designed to lift/move different components, the integrated force analysis showed a statistically different physical demand for different workstations.

3) *The integrated and peak forces analyses will show that a statistically significant difference in force demands can be present between different operators for the same given workstation.*

The current study revealed the presence of several statistically significant differences between operators, in fact both peak and impulse forces were shown to be different between operators for the same given workstation and therefore, the null hypothesis is rejected, accepting this hypothesis. Through this study differences have been related to the different strategy that each operator could adopt. Moreover, different strategies could be related to operators' anthropometric data and level of experience. Operators gain experience while working in a manufacturing environment and individual performance are progressively improved (Argote et al, 1990). In this study, it was not possible to correlate differences between operators to experience level or anthropometric data. However, through axis contribution analysis, it was possible to establish that, in numerous cases, operators used diverse strategy to perform the sub-task.

6. *Conclusions*

The current study evaluated the standard FCA method to measure force demands required to operate lift-assist devices used during automotive assembly. The evaluation was completed by comparing this methodology to a novel methodology that employs an instrumented handle to measure applied hand forces in three dimensions, and in real-time during assembly production.

In conclusion, the current study revealed the 3DDHM method provides a more compressive understanding of the force exertions, and thus the required physical demand, during the operation of a lift-assist than the STD method. Specifically, the STD method analyzes the job task considering only the peak forces reached during a simulation of the job, whereas the 3DDHM methodology allows for performing analyses considering the peak forces, the impulse forces, the direction of the effort, and the duration of the effort. Furthermore, another advantage of the 3DDHM method is the ability to record forces during real assembly operations and not on a simulated static analysis of the job task.

To sum up, the main conclusions formulated by the current study are:

- The STD method measures the magnitude of the effort in one pre-identified direction, while the 3DDHM method measures the effort magnitude, the effort direction, and the effort duration.
- Forces to operate lift-assist device are not purely horizontal, vertical components are usually present and must be taken into account.
- Different operators could perform the same job-task employing different strategies, and therefore performing different efforts.
- An integrated force analysis would lead to associate a single value to each workstation to compare it to others or ergonomically evaluate it, even though an acceptance limit is not yet available in literature.

6.1 Implications for industry

Ergonomic analyses to estimate the injury risks associated with a workstation are extremely important in today's manufacturing world. To correctly estimate the injury risk, physical demand and workers' capacity must be precisely measured or estimated. Much attention should be focused on the definition of the demand, the assessment of the specific demand, and the quality of the tests employed (Bos et al., 2002). For this reason, the 3DDHM method appeared to be able to provide much more accurate and complete information about the real physical demands of the job task. Correspondingly, it is clear that the 3DDHM methodology would be much more efficient for a company that wants to achieve a great level of precision in the estimation of their workstations' physical demands. Furthermore, the current study focused on evaluating the different methodologies for measuring the force demand and not on the establishment of acceptable limits of human capacities. Future research should investigate the possibilities of using this method to create human capability limits based on force impulse recordings.

However, if a company does not utilize the instrumented handle in their ergonomic evaluation process, the current study showed two fundamentally important aspects of ergonomic force data processes. Firstly, the forces needed to move a lift-assist device are not purely horizontal, but a vertical component is usually present, and must be considered. Secondly, the measurements performed on a simulation of the job cannot be considered as valid and precise as direct force measurements performed during daily assembly-line operations. These two elements have been identified as the most important causes of erroneous STD measurements.

Furthermore, the process workstation evaluation should not be performed only by the ergonomist at the plant level. This study has highlighted the physical demands associated with a common task that is performed repetitively during automotive assembly, and lends to the focus moving to more of a proactive approach during the design of the workstations, rather than the reactive plant level evaluation. To accomplish the proactive approach, a shared effort between lift-assist device manufacturer, ergonomists and industrial engineers would lead to better ergonomically designed devices. With knowledge of the effort required to use their lift-assist during real-time assembly operations, manufactures can re-engineer their assists to reduce the physical demand to workers that are using them. However, this can only be achieved with the utilization of new innovative technologies, like the 3DDHM, to obtain the relevant end-user information, as well as the commitment of all of the parties involved.

6.2 Future research directions

Future studies should be conducted with a further improved the level of accuracy and reliability of the 3DHHM method instrumentation. Firstly, a two-hands recording would dissipate any doubts about the similarity of recordings between different hands and it could be interesting to establish if for some workstation there is a hands unbalance. Secondly, a gyroscope could be added to the sensor in handle to avoid any possible imprecision due to a temporary inclination of the handle different than the neutral position. Lastly, a motion capture system should be employed along with the handle, to record the kinematics (i.e. movements performed) of each operator while performing the job task. Doing so, the postures assumed by the operators while performing the job-task can be known and considered during further ergonomic analysis.

Moreover, other analyses could be interesting to be performed: operators could perform different efforts according to the moment of the day in which they are recorded; a difference between the efforts measured at the start and, at the end of the shift could be monitored. At the same time, an FFT (Fast Fourier Transform) analysis might be performed on the data collected through the current study in order to information, such as the vibrations experienced by operators while operating a lift-assist device during automotive final assembly.

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