2018-08-03

Biomechanical Analysis of Accurately and Carefully Placing an Aerospace Avionics Box in Restricted Space

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UNIVERSITY OF MIAMI

BIOMECHANICAL ANALYSIS OF ACCURATELY AND CAREFULLY PLACING AN AEROSPACE AVIONICS BOX IN RESTRICTED SPACE

By

Damon Burns Stambolian

A DISSERTATION

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements for
the degree of Doctor of Philosophy

Coral Gables, Florida

August 2018

UNIVERSITY OF MIAMI

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STAMBOLIAN, DAMON BURNS (Ph.D., Industrial Engineering)
Biomechanical Analysis of Accurately and Carefully Placing an Aerospace Avionics Box in Restricted Space (August 2018)

Abstract of a dissertation at the University of Miami.

Dissertation supervised by Dr. Shihab Asfour.
No. of pages in text. (96)

The design of a spacecraft has many trade-offs to reduce its mass, which typically result in reduced work space for the installation of Line Replaceable Units (LRU). One common LRU in aerospace vehicles is the avionics box found in the space shuttle. To prevent damage to cold plates, the installation of these boxes requires designing for accurate and careful placement, yet there are no standards to follow nor studies to consider for designers concerning human limitations for installing boxes accurately and carefully. In the literature, there are an abundance of lifting studies; however, there are only a few studies that have placed a box in restricted space or on a target as a constraint. Of those studies, only three of those studies have looked at the biomechanics, and none of those studies have looked at factors affecting the Placement Control (accurate and careful placement) of a box on a target in restricted or unrestricted space. Thus, the focus of this study is to determine the biomechanical stresses and the human performance metrics for Placement Control (accurate and careful placement) of a box on target in restricted space.

ACKNOWLEDGMENTS

Above all, praise and thanks to God for accomplishing this Ph.D. I am so very blessed and honoured to be studying under my great advisor Dr. Shihab S. Asfour, always so wise with kindness and integrity, providing everything needed for uniqueness and success, pushing me to do better and knowing when to give me some light in the tunnel to keep me going; and I am also blessed with my Dissertation Committee members: to Dr. Moataz Eltoukhy always providing the precise guidance to help us with the key decisions for the research, and with the development of both biomechanical models, we had many accomplished good times in the biomechanics laboratory; to Dr. Murat Erkoc whom gave me encouragement while I was spending late night hours on campus; to Dr. Arzu Onar for being so kind and for all the expert statistics direction and diligence for the statistical analysis and for the performance metrics, and for her patience for preciseness to make this a significant research, and to Dr. Tim Barth always encouraging me saying a Ph.D. is a marathon. I am so blessed with their encompassing intelligence and our forever relationships. To Dr. Khaled Zakaria Abdel Rahman always quick to help us, to Augusto Roca, Dr. Pete Lisman, and to dependable Sara Botross, and Pablo Escobar and all the lab assistants, and the student subjects. To my intelligent father Haritun Reagh Stambolian and wise mother Dorothea Ann Stambolian who taught me to love and trust God always; and to my wife Charlene Stambolian to energize me to complete the Ph.D., to my brother Carson Haritun Stambolian the attorney minded one, to my sister Teri Lenora Stambolian the analytical minded one, and to my sister Gina Reagh Stambolian the strong and cheerful one. To Dr. Shannon Roberts for mentoring me as “Dr. D” and reviewing the dissertation, to Dr. Gena Henderson for encouraging me with the Ph.D. and mentoring me as Human

Factors Engineer at NASA, to Dr. Michael Bell, Dr. Karim Courey, Tim Honeycutt, Roger Mathews, Charlie Fink, Marcia Groh-Hammond, Maritza Yepremian, and to Tim Adams "NASA Reliability Guru", and to all others that helped me in so many ways. To the Anybody Group, especially Moonki Jung, Pavel Galibarov, and Søren Tørholm. Thank you so much to the University of Miami's Biomechanics Research Group and National Aeronautics and Space Administration (NASA) for partially funding this research. Last but not least to Roger from Barnes and Nobles who would crush a plastic cup behind his back to make it sound like his back was cracking. He would say, "every day you are getting closer and closer to Miami" - meaning closer and closer to completing the Ph.D. I love all of you. God Bless and always God's Speed to all of you.

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INTRODUCTION

The design of a spacecraft has many trade-offs to reduce its mass, which typically result in reduced work space for the installation of Line Replaceable Units (LRU). One common LRU in aerospace vehicles is the avionics box found in the space shuttle. To prevent damage to cold plates, the installation of these boxes requires designing for accurate and careful placement, yet there are no standards to follow nor studies to consider for designers concerning human limitations for installing boxes accurately and carefully. In the literature, there are an abundance of lifting studies; however, there are only a few studies that have placed a box in restricted space or on a target as a constraint. Of those studies, only three of those studies have looked at the biomechanics, and none of those studies have looked at factors affecting the Placement Control (accurate and careful placement) of a box on a target in restricted or unrestricted space.

One critical need for careful and accurate placement in restricted space is the placement of avionics boxes in the space shuttle orbiter avionics bay, which was how the idea came for this study. Over the years, there have been many occurrences of damage to space shuttle orbiter cold plates during removal and replacement of avionics boxes. Each cold plate in the space shuttle orbiter costs an average of $362,500 (Stambolian et al., 2012), which is a substantial expense for NASA if damaged repeatedly over time. The space shuttle avionics boxes were installed on multiple shelves, and there were multiple boxes placed close to one another on each shelf. See Figure 1.

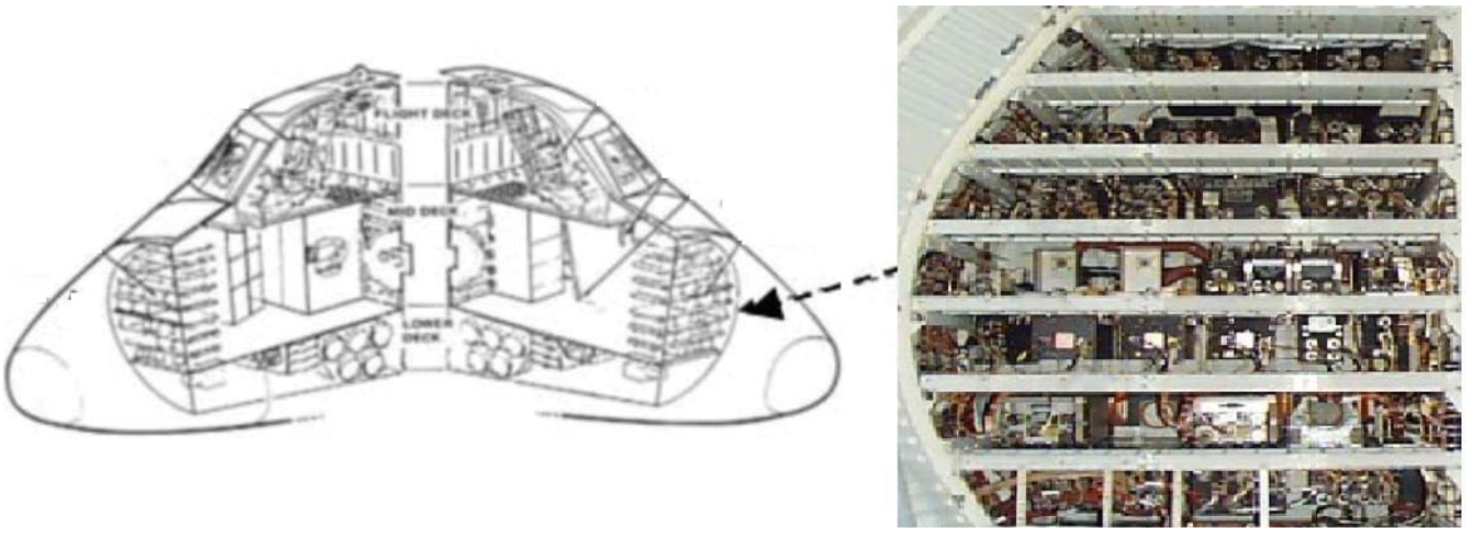

Figure 1. Avionics bay and boxes in space shuttle orbiter

Figure 2 shows an avionics box assembled on a cold plate and areas of damage marked on the cold plate. When there is lack of placement control, the cold plate could be damaged if the avionics box is placed less-carefully, or damage can occur during repositioning the box after it has been placed less-accurately. With a box on top of the cold plate, the damage to the cold plate can go undetected, which potentially could allow the cold plate to leak fluids while in space, resulting in a loss of mission. Therefore, it is critical to carefully and accurately place the avionics box on the cold plate.

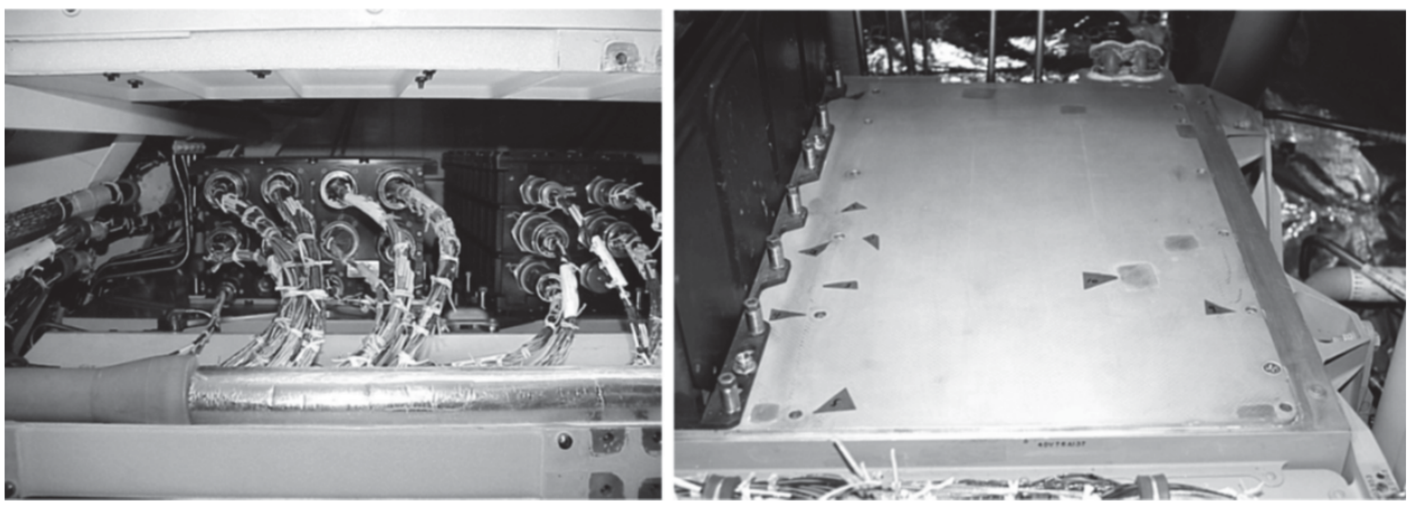

Figure 2. Avionics box and cold plate

Since human capabilities vary, the avionics box will not be placed the same way by everyone. Therefore, it is important to understand what the limitations of the humans are when it comes to accurately and carefully placing the box. More important than the damage to flight hardware is the injury to the humans. Given that this hardware is critical to mission success, the technicians will do their best to place the avionics box accurately and carefully on target. Striving to do this increases the chance of overexertion and/or increases stresses to the lower back.

Thus, the focus of this research is to determine performance metrics for Placement Control (accurate and careful placement) of a box in restricted space, by understanding the association between these factors: box weight, shelf height, and shelf space. The objective is to determine if restricted space reduces the human's capability of Placement Control (accurate and careful placement), and to determine if the restricted space has an influence on stresses to the spine. It is hypothesized that restricted space will reduce Placement Control (accurate and careful placement), and that restricted space will also increase stress to the spine.

Keywords: standards, equipment design, manual handling, Placement Control, human error, biomechanics, human factors, ergonomics

Outline of Objectives:

- How accurately the avionics box can be placed on target
- How carefully the avionics box can be placed on target
- How much time it takes to place the box on target
- What are the biomechanical stresses to the lower back
    - Develop and validate biomechanical model

CHAPTER 2 LITERATURE REVIEW

Only a few studies have looked at placing a box on a target or within restricted clearance. Of those studies, none have looked at the human's ability to accurately and carefully place the box on target and in restricted or unrestricted space. No reported research was found in direct relation to controlled placement (Herrin et al., 1974). No studies have been found on the effects of workspace on the classical lifting and lowering tasks (Drury, 1985). In the paper "Spatial Restraints and Intra-Abdominal Pressure," there is a section on accuracy referencing Sabry's recommendations that state, "regardless of load/target dimension, there should be a 5cm clearance on either side of any load for reasonable level of accuracy" (Ridd, 1985). Psychophysical and physiological effects from work space around a box have been studied (Wang, 1987). Tight clearances around the box resulted in less lifting weight desired by the subject (Mital & Wang, 1989). These studies had referenced clearance restrictions to the top and sides of the box, but did not require placement on a target. Other studies used the physiological and psychophysical approach to determine the rate of perceived exertion (RPE), and the physiological cost (heart rate, oxygen uptake, and ventilation volume) at low frequency lifting with reduced shelf access clearance (Kumar et al., 1993). Biomechanical and abdominal measurements were taken to determine if restricted clearances, asymmetry, and reduced head room significantly affect biomechanical stresses (Kumar, 1999). The Borg's Scale, the Visual Analogue Scale, and Body Part Discomfort Rating were used to determine the relative and absolute sensitivity (Kumar et al., 1999). This was done to determine if these psychophysical techniques could measure the physical stress differences in: unlimited and limited headroom, limited clearance

(5mm and 10 mm), and asymmetric and symmetric lift directions. Physiological (heart rate, caloric cost, and ventilation volume) and the psychophysical (Borg scale, visual analog scale, body part discomfort rating) were measured during resting, palletizing, and recovery (Kumar et al., 2000). Workplace job demands, including lift rate, box weight, Placement Control, mental concentration, and task asymmetry; may impact any or all the biomechanical responses; trunk kinematics, trunk kinetics, and muscle activity. See Figure 3. In this study, it was required for the box to land on a target within 1.27 mm around all sides of the box. When the box was not placed accurately, it was not recorded nor analyzed. (Davis, 2001; Davis et al., 2002; Davis and Marras, 2003).

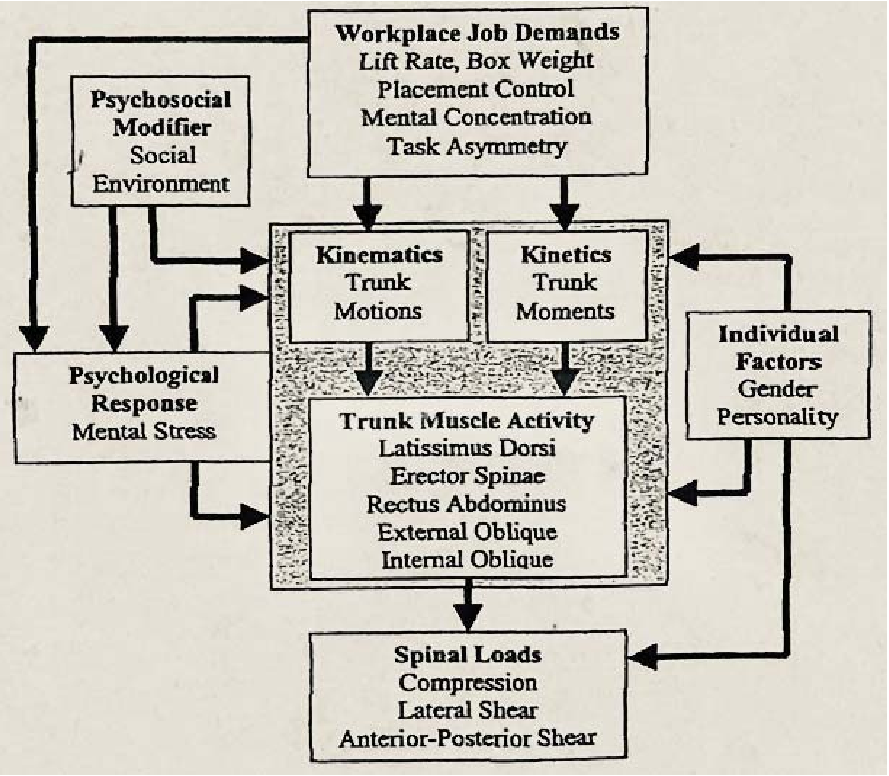

Figure 3. Davis 2001 - Placement Control is a workplace job demand

Interactive effects of physical and mental workload on subjective workload assessment were used to evaluate the subjective assessment of physical and mental workload (DiDomenico, 2003). Controlled placement was used to evaluate physical performance. The target was a 2.54 cm clearance around all sides of the box target. All the subjects had no trouble placing the box in the target zone for every placement. Precision placement constraints and cognitive distractions on upper body kinematics, trunk muscles, and spine loading were studied (Beach et al., 2006). Four different tasks used were: control, cognitive distraction, precision placement, and combined cognitive and precision placement. A significant limitation in this study was not measuring the precision placement that the subjects performed. In summary, there were no studies that measured nor analyzed the Placement Control (accurate and careful placement) of a box on target in open or restricted space. No studies measured nor analyzed the biomechanical stresses while placing a box on target in restricted space. See Table 1.

Table 1. Summary of studies

Studies	Restrictions to sides of box	Restrictions to top of box	Placed on target	Accurate placement	Careful placement	Biomechanical stresses
Sabry			X	X		
Wang Luh-Wang	X	X				
Shrawan Kumar	X					X
Kermit Davis			X			X
Angela Terese DiDomenico			X			
Tyson Beach			X			X
*Damon Stambolian	X	X	X	X	X	X

**Current Study*

Other applications for placement control

The same type of box is used in aerospace, trains, planes, and ships. Other activities where accurate and careful placement is required for delicate objects could include high priced art items on shelves, or placing a baby carefully. In the automotive industry, the engine cylinder head is placed carefully onto the motor block. The cylinder head needs to be accurately aligned with the mounting holes, and because there is a gasket between the cylinder head and the block, the installer needs to place the head delicately during the installation.

Related studies to placement control

The following section will further describe the related studies to Placement Control. The areas covered are: destination height, clearances for box, box hand location and box trajectory, box dimensions, box weight, box material, destination monitoring, lifting direction. lift frequency, subject (gender, age, and work experience), and biomechanical models.

Destination height

In previous studies, the destination heights varied from 27" to 60". See Table 2. The study that best represents the current work was by Shrawan Kumar which had a shelf height of 49". Because the space shuttle has many different shelf heights, it is not practical to study each shelf height, therefore, a range from 30" and 50" was used in this Placement Control research.

Table 2. Destination height

	Destination height
Wang Luh-Wang (1987)	Floor to 32", and 32" to 60"
Anil Mital and Luh-Wang (1989)	Floor to 0.81m, 0.81 m to 1.52 m. 31.9" to 59.8"
Anil Mital (1989)	Floor to knuckle, knuckle to shoulder, shoulder to reach
Shrawan Kumar, et al., (1993)	125 cm high shelf. 49.2"
Shrawan Kumar (1999)	Ground to shelf at 125 cm high. 49.2"
Shrawan Kumar, et al., (1999)	Shelf 132 cm high 51.6"
Shrawan. Kumar, et al., (2000)	Shelf 125 cm high. 49.2"
Kermit G. Davis (2001, 2002, 2003)	Start at 80 cm to 105 cm. 41.3"
Angela Terese DiDomenico (2003)	750 mm. 29.52"
Tyson A.C. Beach. et al., (2006)	0.75 m. 27"
Damon B. Stambolian. et al., (2011)	Floor to 30" and floor to 50"

Clearances for box

Table 3 lists the clearances for the restrictions and targets from the previous studies. The clearances around the box in the space shuttle varied. Some boxes were closer to each other, and some boxes had more clearance above the box. Investigating different clearances was not in the scope of this current research. Federal Aviation Administration (FAA) Human Factors Design Standards (HFDS) were used to determine the clearances for determining the shelf space in this Placement Control research.

Table 3. Clearances for box

	Location of Clearance	**Clearance**
Wang Luh-Wang (1987)	Top and sides of box	Open, loose (box plus 5%, above box on shelf 0.65", each side 0.6"), tight (box plus 1%, above box on shelf 0.13" each side 0.12"
Anil Mital and Luh-Wang (1989)	Sides of box	Unrestricted, loose 15mm (0.591"), and tight 3mm (0.118")
Anil Mital (1989)	Sides of box	Unlimited, 15mm (0.591"), 3mm (0.118")
Shrawan Kumar, et al., (1993)	Sides of box	15 mm (0.591"), 20 mm (0.787"), 25 mm (0.984") and 30 mm (1.18")
Shrawan Kumar (1999)	Sides of box	5 (0.197") and 10 mm (0.394"), unrestricted headroom, and headroom's adjusted to 90% and 80% of the subjects
Shrawan Kumar, et al., (1999)	Sides of box	5mm (0.197") and 10 mm (0.394")
Shrawan. Kumar, et al., (2000)	Sides of box	5 mm (0.197") and 10 mm (0.394")
Kermit G. Davis (2001)	Bottom of box	General and 1.3 cm (0.512")
Kermit G. Davis, et al., (2002)	Bottom of box	General and 1.3 cm (0.512")
Kermit G. Davis and William S. Marras (2003)	Bottom of box	General and 1.3 cm (0.512")
Angela Terese DiDomenico (2003)	Bottom of box	2"
Tyson A.C. Beach, et al., (2006)	Bottom of box	1.3 cm (0.512")
Damon B. Stambolian, et al., (2011)	Top of box, sides of box, and bottom of box	Top and sides of box determined from FAA Standards. Target is same dimensions as bottom of box.

Box hand location and box trajectory

In Wang Luh Wang's study, the preferred (right) hand was at the bottom corner and the other hand at the diagonal top corner, and the box was inserted into the restricted clearance at the front of the shelf. See Figure 4.

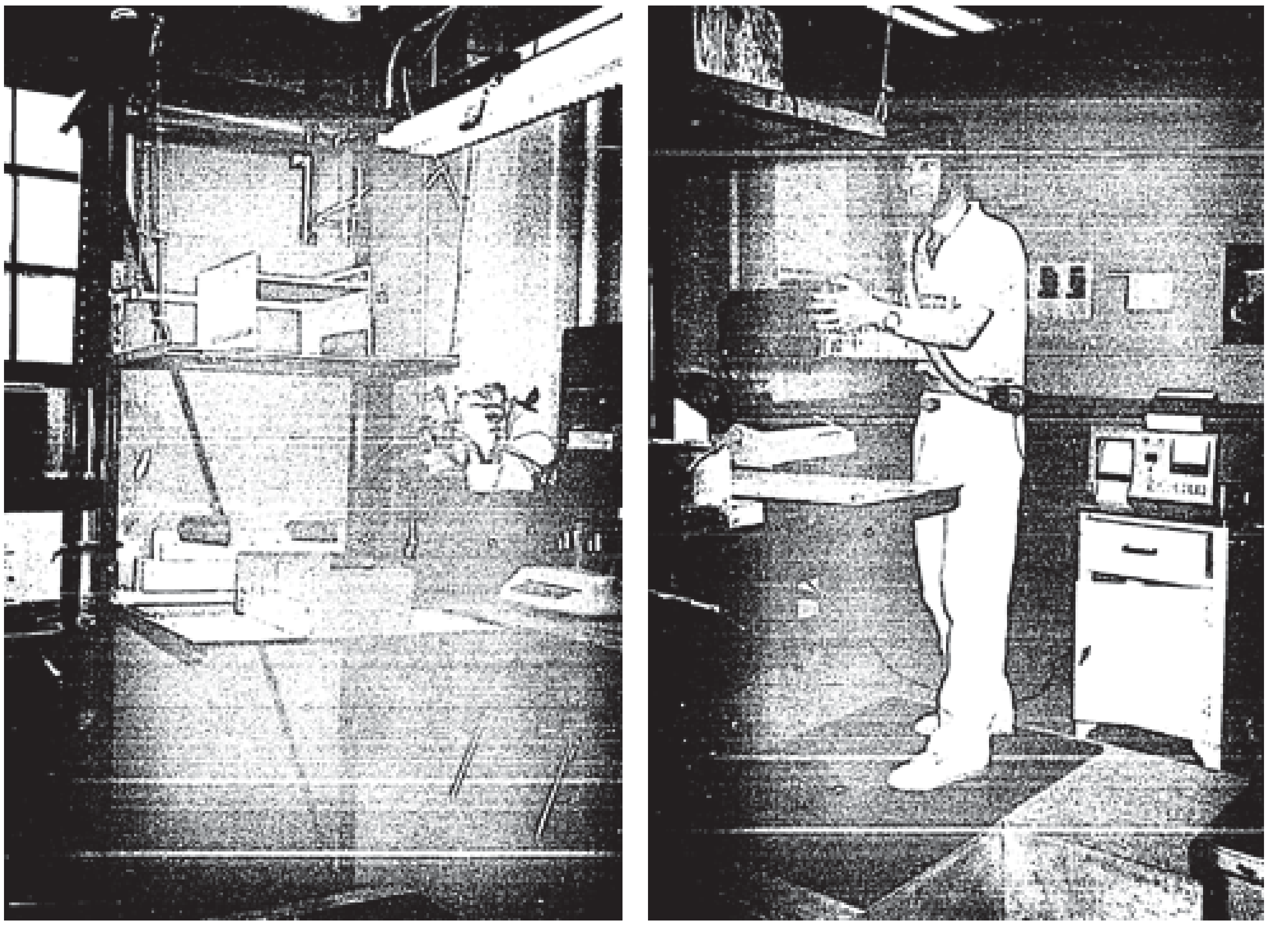

Figure 4. Wang Luh-Wang hand location and box trajectory

With Shrawan Kumar, the boxes were set up for both cases with and without handles. The handles were cutouts in the side panels at the top middle. When the handles were not used, the box was held with the left hand on the far left, top corner and the right hand near the right side, bottom corner. There were no restrictions at the top of the box. The box trajectory in this lift was placing the box between the two restrictions to the sides of the box. Shrawan Kumar used this device in several studies. See Figure 5.

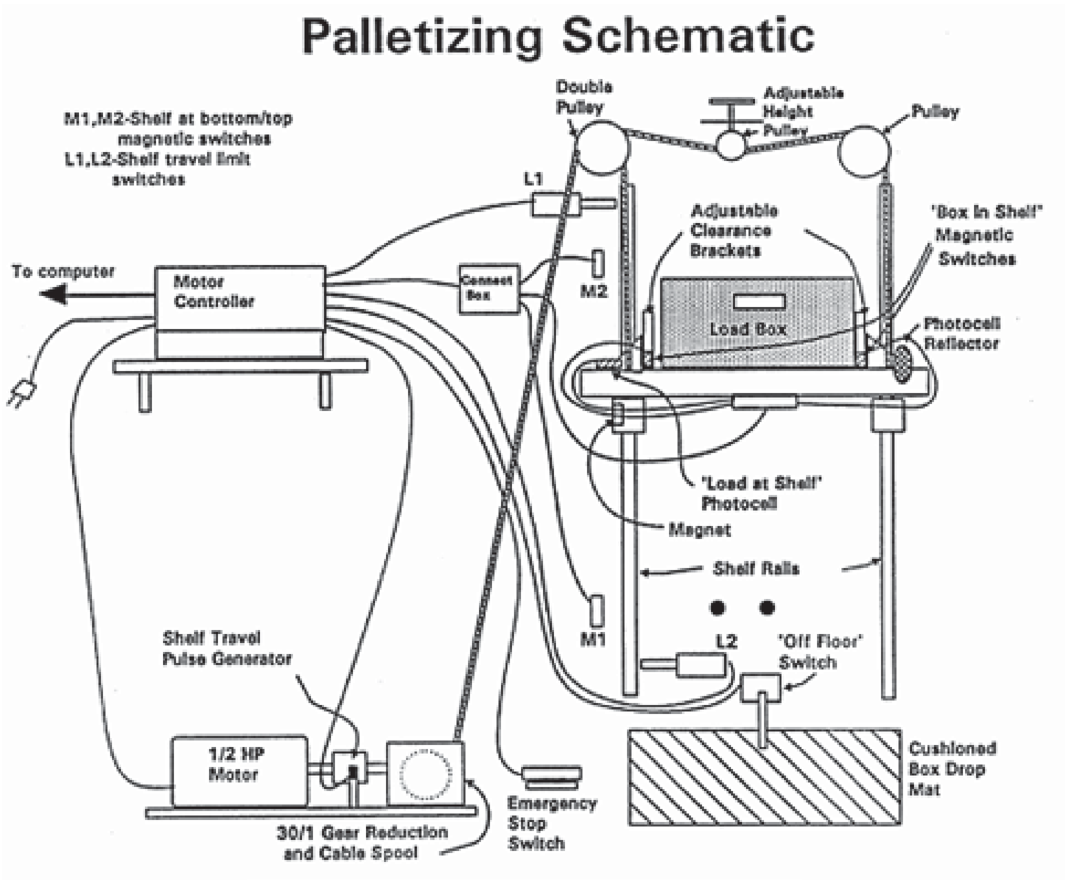

Figure 5. Shrawan Kumar hand location and box trajectory

With Kermit Davis, the boxes had no handles. The box was held at opposite corners from the underside of the box, and the box was placed on a target. See Figure 6.

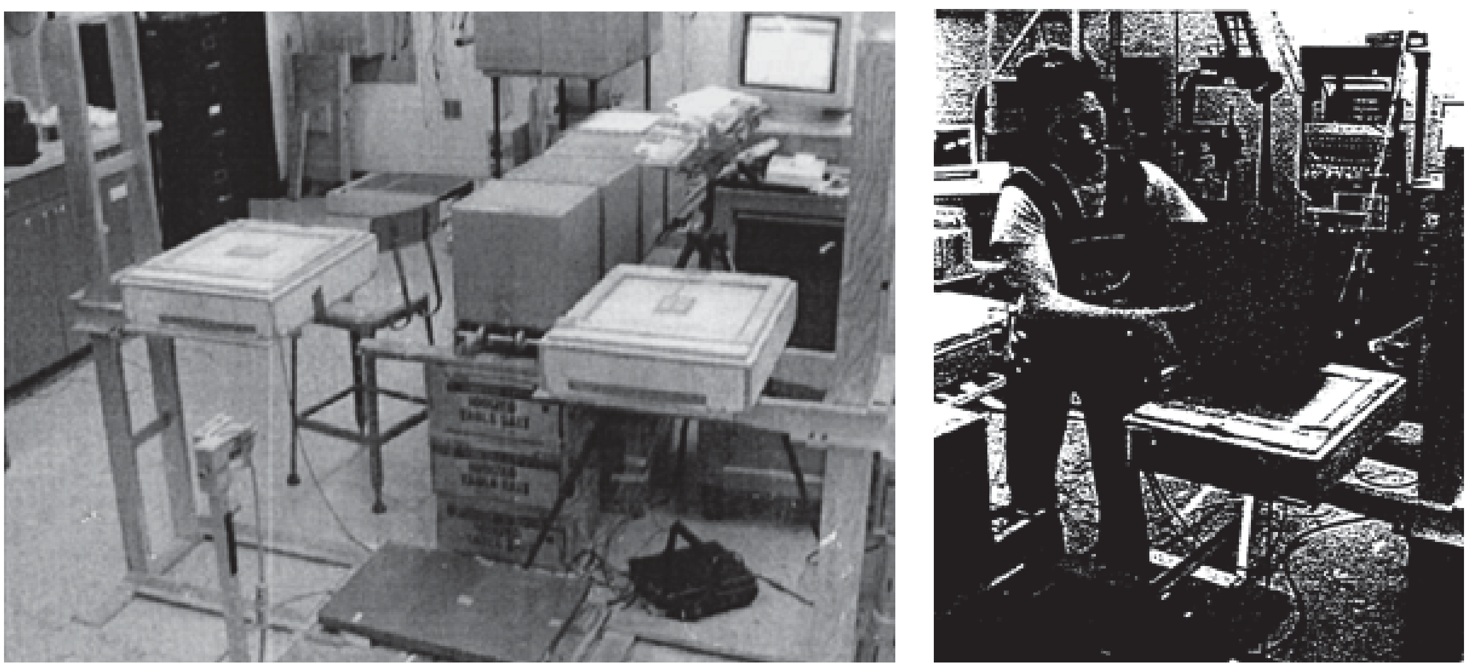

Figure 6. Davis hand location and box trajectory

In Angela DiDomenico's dissertation work, the box had cutouts for handles, and the boxes were held with both hands. The box was placed on the shelf. See Figure 7.

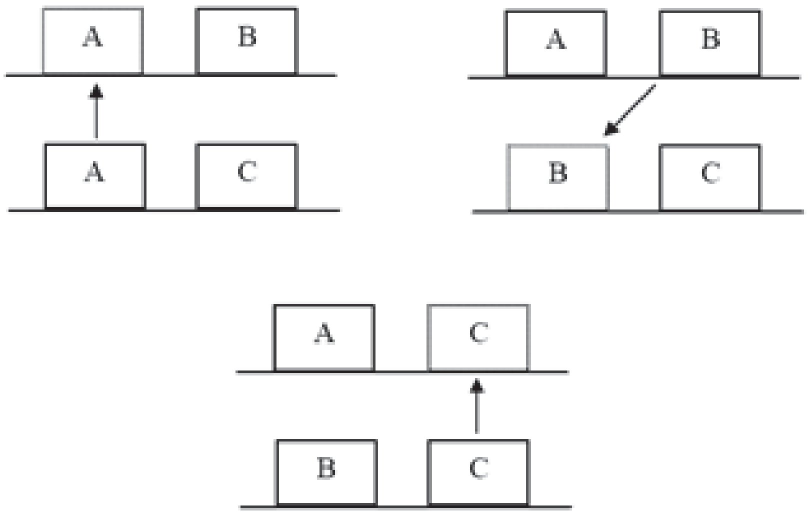

Figure 7. DiDomenico hand location and box trajectory

With Tyson Beach, the hands grasped a jig with a weight attached to it. The weight was lifted and placed on the table. See Figure 8.

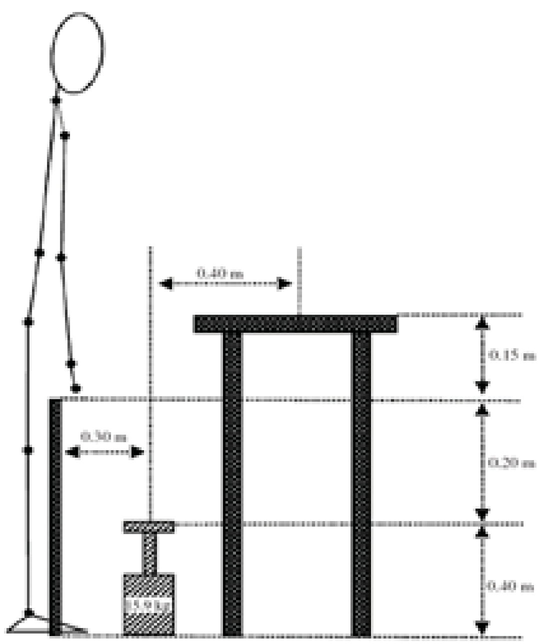

Figure 8. Beach hand location and box trajectory

For the space shuttle boxes and this Placement Control research, the boxes are held by the palms of the hands pressing against the sides of the box.

Box dimensions

Box sizes range from 12" to 24" wide, 6.5" to 24" high, and 11.8" to 24" long. See Table 4. For the space shuttle, the boxes are various sizes. See Table 5.

Table 4. Box dimensions

	Height	Width	Length
Wang Luh-Wang (1987)	6.5" (16.51 cm)	12" (30.48 cm)	18" (45.72cm)
Anil Mital (1989)	30.48cm (12") 45.72 cm (18") 60.96cm (24")	30.48cm (12") 45.72 cm (18") 60.96cm (24")	30.48cm (12") 45.72 cm (18") 60.96 cm (24")
Shrawan Kumar, et al., (1993)	30 cm (11.8")	46 cm (18.1")	30 cm (11.8")
Shrawan Kumar (1999)	30 cm (11.8")	46 cm (18.1")	30 cm (11.8")
Shrawan Kumar, et al., (1999)	30 cm (11.8")	46 cm (18.1")	30 cm (11.8")
Shrawan. Kumar, et al., (2000)	30 cm (11.8")	(46 cm (18.1")	30 cm (11.8")
Kermit G. Davis (2001)	31 cm (12.2")	31 cm (12.2")	31 cm (12.2")
Kermit G. Davis and William S. Marras (2003)	31 cm (12.2")	31 cm (12.2")	31 cm (12.2")
Angela Terese DiDomenico (2003)	~60cm (23.6")	~60cm (23.6") (distance between hands was 600mm)	~60cm (23.6")
Tyson A.C. Beach, et al., (2006)	Jig, (no dimensions given)	Jig	Jig
Damon B. Stambolian, et al., (2011)	7.8"	7.6"	19.7"

Table 5. Space shuttle orbiter avionics box dimensions

Box type	Dimensions, inches (cm)		
	Height	Width	Length
AP-101S	7.62 (19.3)	10.2 (25.9)	19.55 (49.6)
IMU	10.28 (26.1)	11.5 (29.2)	22 (55.88)
IOP	7.62 (19.3)	10.2 (25.9)	19.55 (49.6)
CPU	7.62 (19.3)	10.2 (25.9)	19.55 (49.6)
HAINS	9.24 (23.5)	8.49 (21.6)	22 (55.9)
Assent Thrust Controller	7.6 (19.3)	10 (25.4)	20 (50.8)
MDM	7 (17.8)	10 (25.4)	13 (33)
ASA	6.4 (16.3)	9.12 (23.2)	20 (50.8)
TACAN	7.62 (19.4)	7.62 (19.4)	12.53 (31.8)
MMU	7.6 (19.3)	11.6 (29.5)	15 (38.1)
ADTA	4.87 (12.4)	4.37 (11.1)	21.25(53.9)
MSBLS	8.25 (21)	5 (12.7)	16.6(42.2)
Bus Amplifier	7 (17.8)	6 (15.2)	5 (12.7)
RF Assembly	7 (17.8)	3.5 (8.9)	10.25 (26)
Radar Altimeter	3.13 (8)	8.38 (12.3)	7.41 (18.8)

Box weight

For the space shuttle, the boxes weights ranged from 4.5 to 64 pounds. See Table 6. The contents of the box determine its weight, so it is possible to have a similar size box with different weight. For example, the ASA box is 6.4 x 9.12 x 20, and its weight is shown as 30.2 pounds, but the AP-101S box is 7.62 x 10.2 x 19.55 and its weight is shown as 64 lbs. Both boxes are similar in size, however their weights differ. The box weights lifted in the related studies are shown in Table 7. The weights ranged from no weight to 53.8 lbs.

Table 6. Space shuttle the boxes weights

Box type	Weight, lbs.(kg)
AP-101S	64 (29.09)
IMU	58 (26.36)
IOP	57 (25.09)
CPU	57 (25.09)
HAINS	43.5 (19.77)
Assent Thrust Controller	39.9 (18.13)
MDM	36.7 (16.68)
ASA	30.2 (13.72)
TACAN	30 (13.63)
MMU	22 (10)
ADTA	19.2 (8.72)
MSBLS	17.5 (7.95)
Bus Amplifier	7.5 (3.40)
RF assembly	6 (2.72)
Radar altimeter	4.5 (2.05)

Table 7. Box weights in related studies

	Box lifting weights
Wang Luh-Wang (1987) [4], Anil Mital and Luh-Wang (1989) [5]	Unrestricted weights: (males 20.52 kg (45.144-lb) mean, 3.66 kg (8.052-lb) sd), (females 13.42 kg (29.524-lb) mean, 2.42 (5.324-lb) sd) Loose weights: (males 18.98 (41.756-lb) mean, 4.86 (10.692-lb.) sd), (females 12.35 (27.17-lb) mean, 2.27 (4.994-lb) sd) Tight weights: (males 18.56 (40.832-lb) mean, 3.87 (8.514 -lb) sd), (females 11.97 (26.334-lb) mean, 1.82 (4.004-lb) sd)
Shrawan Kumar, et al., (1993)	11 kg (24.2 lbs.) and 22 kg (48.4 lbs.)
Shrawan Kumar (1997-1999)	MAW 22 kg
Shrawan Kumar, et al., (1999)	22 kg (48.4 lbs.), 4 kg more than RWL for women
Shrawan. Kumar, et al., (2000)	22 kg (48.4 lbs.)
Kermit G. Davis (2001) Kermit G. Davis, et al., (2002), Kermit G. Davis and William S. Marras (2003) [13]	6.8 (14.96 lbs.) and 11.4 kg (25.08 lbs.)
Angela Terese DiDomenico (2003)	No load, low 8% of body weight, med 14% of bw, and high 20% of bw

Tyson A.C. Beach. et al., (2006)	15.9 kg (34.98 lbs.)
Damon B. Stambolian, et al, (2011)	15, 30, 45 pounds

The box weight for the Aeronautical Radio Incorporated (ARNIC) 404 Standards ranges from 3 to 60 pounds. The weight and size of the box used in this Placement Control research was determined by using the dimensions from the space shuttle, previous studies, and the ARNIC 404 standards. See Figure 9.

ATR SIZE	Usual Weight Range		E		F	
	Pounds	Kg	Inches	mm	Inches	mm
Dwarf ATR	3 - 7	1.4-3.2	5.25	133.4	.75	19.1
1/4 ATR-Short	7 - 12	3.2-5.4	5.25	133.4	.75	19.1
1/4 ATR-Long	8 - 30	3.6-13.6	8.19	208.0	.75	19.1
3/8 ATR-Short	5 - 15	2.3-6.8	5.25	133.4	1.25	31.8
3/8 ATR-long	12 - 35	5.4-15.9	8.19	208.0	1.25	31.8
1/2 ATR-Short	8 - 18	3.6-8.2	5.25	133.4	2	50.8
1/2 ATR-long	18 - 40	8.2-18.2	8.19	208.0	2	50.8
3/4 ATR-Short	10 - 30	4.5-13.6	5.25	133.4	3	76.2
3/4 ATR-Long	20 - 45	9.1-20.4	8.19	208.0	3	76.2
1 ATR-Short	20 - 45	9.1-20.4	5.25	133.4	4.25	108.0
1 ATR-Long	25 - 60	11.4-27.2	8.19	208.0	4.25	108.0
1-1/2 ATR	40	18.1	8.19	208.0	6.44	163.6

Figure 9. ARNIC standards

The box weights for this study were chosen as 15, 30, and 45 pounds. This covers the span with the space shuttle boxes and boxes from past studies. The weight is distributed uniformly in the box by using metal plates spaced evenly in the box.

Box material

The boxes used in these studies were wooden or cardboard boxes. The boxes used in this Placement Control research are avionics boxes built to ARNIC specifications. See Table 8. These built-to-specification boxes are mostly rectangular and made of metal.

Table 8. Box material

	Box material
Wang Luh-Wang (1987)	Wooden container
Shrawan Kumar, et al., (1993)	Wooden box
Shrawan Kumar, et al., (1999)	Wooden box
Shrawan. Kumar, et al., (2000)	Wooden box
Kermit G. Davis (2001)	Corrugated cardboard
Kermit G. Davis and William S. Marras (2003)	Corrugated cardboard
Tyson A.C. Beach, et al., (2006)	Custom hand jig with a weight lifting plate
Damon B. Stambolian, et al., (2011)	Aluminum built to ARNIC specifications

Destination monitoring

Wang Luh Wang did not have a mechanical method to record how the box was being placed; however, subjects in that study stated verbally that tight space clearance was the most difficult placement as compared to the no-space clearance. In the Shrawan Kumar study, the apparatus could record the time that the leading edge reached the front part of the clearance brackets to the time the box reached its resting position. Kermit Davis used a buzzer to indicate when the box was not placed correctly. Incorrect placement required repeating of the lift. Kermit Davis also attempted to emulate a poor social environment by trigger switching the buzzer to simulate that the box was not placed correctly. However, this part of the analysis was terminated since it was difficult to get the correct buzzer timing upon box placement. In Angela DiDomenico's study, all of the subject trials had no difficulty in performing this placement. In the Tyson Beach study, the precision of the jig placement was verbally indicated to the subjects to help them remain focused on the task; however, as referenced in this paper, one of the limitations of this study was that a measurement of the precision placement was not actually done. For the research in this dissertation on Placement Control, the placement accuracy and control will be determined by reviewing the trajectory of the markers on the box in relation to the markers placed on the shelf.

Lifting direction

The lifting direction in most of the significant studies was in the sagittal plane. In this Placement Control research, the lift is sagittal based on discussions with the technicians that install avionics boxes in the space shuttle. See Table 9.

Table 9. Lifting direction

	Lifting direction
Wang Luh-Wang (1987)	Sagittal
Anil Mital and Luh-Wang (1989)	Sagittal
Anil Mital (1989)	Sagittal and asymmetrical
Shrawan Kumar, et al., (1993)	Sagittal symmetrical and 45 degrees asymmetrical plane to the right.
Shrawan Kumar (1999)	The two chosen positions for the box were directly in front and at a 45 degrees with respect to sagittal plane.
Shrawan Kumar, et al., (1999)	Sagittal and 45 degrees asymmetrical postures
Kermit G. Davis (2001)	90 degrees asymmetry
Kermit G. Davis, et al., (2002)	90 degrees asymmetry
Kermit G. Davis and William S. Marras (2003)	90 degrees asymmetry
Angela Terese DiDomenico (2003)	Sagittal
Tyson A.C. Beach, et al., (2006)	Sagittal

	Lifting direction
Damon B. Stambolian (2011)	Sagittal

Lift frequency

In the significant studies, the lift frequency ranges from as low as one lift to as many as eight lifts per minute. Shuttle avionics boxes are only lifted once per shift. For this Placement Control research, the boxes were lifted no more than once per two minutes, to allow for the subject to rest. See Table 10.

Table 10. Lift frequencies

	Lift frequency
Wang Luh-Wang (1987), Anil Mital and Luh-Wang (1989)	1 and 4 lifts / min
Shrawan Kumar, et al., (1993)	2 lifts / min
Shrawan Kumar (1999)	3 lifts / min
Shrawan Kumar, et al., (1999)	6 lifts / min
Shrawan. Kumar, et al., (2000)	6 lifts / min
Kermit G. Davis (2001)	2 and 8 lifts / min
Kermit G. Davis, et al., (2002)	2 and 8 lifts / min
Kermit G. Davis and William S. Marras (2003)	2 and 8 lifts / min
Angela Terese DiDomenico (2003)	5 lifts / min
Tyson A.C. Beach. et al., (2006)	7.5 lifts / min
Damon B. Stambolian, et al., (2011)	<1 lift/2 min

Subject gender, age, and work experience

For the studies that included male and female subjects, the number of male and female subjects were equal. The work experience varied from industry to university students. The participants ranged in age between 17 and 40, with most of the studies having subjects age under 30 years. The Placement Control research involved college-age males with no work experience installing avionics boxes. See Table 11.

Table 11. Gender, age, and work experience

	Quantity and gender	Age	Work experience
Wang Luh-Wang (1987)	8 males and 8 females	17 and 40	Students
Anil Mital and Luh-Wang (1989)	8 males and 8 females	Males 23 to 40, females 17 to 29	Volunteers
Shrawan Kumar, et al., (1993)	15 restriction (access) 15 headroom. males	For restriction to access. 31.5, sd-7.1	Industry
Shrawan Kumar (1999)	11 males	Mean 29.1	Industry
Shrawan Kumar, et al., (1999)	10 females 10 males	Male 27.1 sd-4.68, female 24.4 sd-4.01	University students
Shrawan. Kumar, et al., (2000)	21 males	Mean-29.1yrs sd-5.9	Industrial
Kermit G. Davis (2001)	30 males and 30 females	Male, 23.3 sd-3.2. female, 21.3 sd-2.3	University students
Kermit G. Davis, et al., (2002)	30 males and 30 females	Male, 23.3 sd-3.2. female, 21.3 sd-2.3	Subjects
Kermit G. Davis and William S. Marras (2003)	30 males and 30 females	College age	University students
Angela Terese DiDomenico (2003)	15 females and 15 males	20.7 sd-1.15	University students
Tyson A.C. Beach, et al., (2006)	9 males	26 sd-2.8	Volunteers
Damon B. Stambolian, et al., (2011)	20 males	College age	University students

Biomechanical models

The biomechanical models related to the above studies are as follows: Shrawan Kumar used a general inverse dynamics biomechanical model for deriving the external kinetics, and optimization was used for estimating internal muscle forces for these muscles; erector spinae (ES), external obliques (EO), internal obliques (IO), rectus abdominis (RA), latissimus dorsi (LD). Kermit Davis used the lumbar motion monitor, attached to the back of the subject, to obtain the external trunk movements and to estimated trunk external kinetics. Along with the external trunk kinetics, Davis used Electromyography (EMG) of the 5 trunk muscles, ES, IO, EO, RA, LD, for deriving the internal muscle kinetics to derive the total L5/S1 kinetics. Tyson Beach also used the lumbar motion monitor and EMG; however, also included the upper body markers to derive the kinematics for the upper body movements analysis.

Summary of biomechanical models

Table 12. Summary of biomechanical models

	Type of study	**External kinetics**	**Internal kinetics**
Wang Luh-Wang (1987)	Physiological/ Psychophysical	N/A	N/A
Shrawan Kumar, et al., (1993)	Physiological/ Psychophysical	N/A	N/A
Shrawan Kumar (1999)	Biomechanical Lumbar	General inverse dynamics	Optimization
Shrawan Kumar, et al., (1999)	Physiological	N/A	N/A
Shrawan. Kumar, et al., (2000)	Physiological/ Psychophysical	N/A	N/A
Kermit G. Davis (2001)	Biomechanical Lumbar	Lumbar Motion Monitor	EMG
Kermit G. Davis, et al., (2002)	Biomechanical Lumbar	Lumbar Motion Monitor	EMG

Kermit G. Davis and William S. Marras (2003)	Biomechanical Lumbar	Lumbar Motion Monitor	EMG
Angela Terese DiDomenico (2003)	Psychophysical	N/A	N/A
Tyson A.C. Beach, et al., (2006)	Biomechanical Lumbar	Lumbar Motion Monitor	EMG
Damon B. Stambolian, et al., (2011)	Biomechanical	N/A	EMG

CHAPTER 3 DEVELOPMENT OF BIOMECHANICAL MODELS

A Spine Model (S-Model) was developed at the University of Miami using Vicon BodyBuilder (BB) and Nexus. This model only provided external kinetics, and it needed excessive development to include muscles to generate the internal muscle kinetics. At the time the AB GaitFullModel with full body muscles became available, it was decided to cease further development on the S-Model and begin developing the model needed for this research by using the AB Modeling System (Damsgaard et al., 2006). Although the S-Model is an advancement for Vicon models, the AnyBody (AB) Technology was used for the development of the biomechanical model used in this Placement Control research.

Spine Model

The S-Model was developed in BB. The model gives the lumbar joint angles and an approximation of external kinetics at the L5/S1. The joint angles for this model were validated (Stambolian et.al., 2014a). Shown in Table 13 and the corresponding Figure 10, is the comparison of the Vicon Plug-In-Gait (PIG) torso-pelvis angle values, the S-Model L5/S1 angle values, and the literature L5/S1 angle values.

Table 13. S-Model joint angle comparison (degrees)

	PIG Torso/Pelvis	SM L5/S1	Literature L5/S1
Flexion/Extension	71.0	5.7	14.0
Lateral Bending	29.6	1.7	3.0
Axial Rotation	35.4	2.4	1.6

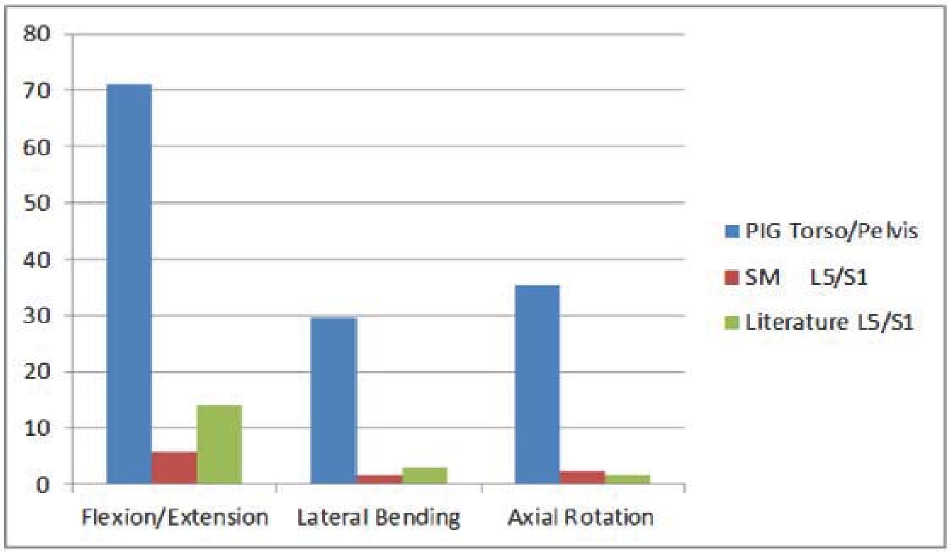

Figure 10. PIG, S-Model, and literature - L5/S1 comparison

During the Range of Motion (ROM), the maximum value for the PIG torso-pelvis angle output for flexion/extension was 71.0 degrees, the corresponding S-Model L5/S1 angle output was 5.7 degrees, and the literature L5/S1 angle value is 14.0 degrees (Pearcy, Portek, and Shepherd, 1984). The maximum value for the PIG torso-pelvis angle output for lateral bending was 29.6 degrees, the corresponding S-Model L5/S1 angle output was 1.7 degrees, and the literature L5/S1 angle value is 3 degrees (Pearcy & Tibrewal, 1984). And, the maximum value for the PIG torso-pelvis angle output for axial rotation was 35.4 degrees, the corresponding S-Model L5/S1 angle output was 2.4 degrees, and the literature L5/S1 angle value is 1.6 degree (Fujii et al., 2007).

Overall, as compared to the PIG torso-pelvis angle values, the S-Model L5/S1 angle values are closer to the literature values by 8.3 degrees as compared to 57 degrees for flexion/extension; 1.3 degrees as compared to 27.9 degrees for lateral bending; and, 0.6 degrees as compared to 33 degrees for axial rotation.

The entire programming code for this model can be found in the Vicon BB online repository. The following describes how the S-Model was developed. The Vicon BB model developed at the University of Miami is based on the open source Vicon Golem model and the addition of the Vicon BB Spine function. The Golem model was chosen because it is similar to the most commonly used closed source PIG model. The Vicon BB Spine function was added to the Golem model to create the lumbar vertebrae. The BB Golem code was modified so the lumbar segments could be added to the model without having to change the existing PIG marker configuration. The L5 axes were created, and the existing sacrum axis were modified to be closer to the anthropometric center. Once the centers were defined, the lumbar vertebra segments were defined using the Spine function. The Spine function requires the location of the first segment and the location of the last segment. The first segment is T10, and the last segment is sacrum. The curvature of the spine can be adjusted by changing the value for length or stiffness variable in the Spine function. With the Spine function and code modifications included in the Golem model, there is an axis at the origin for each vertebrae segment, just as is for all of the other body segments. Once the lumbar and cervical segments were developed, the code for deriving model outputs for each vertebra was developed. First, code was developed for the angle outputs. Adjustments to the code were made so the angles were in the same direction, i.e., L5 angle curves in a similar direction as existing model outputs for spine and neck. It was found that using the Nexus software was an effective way to validate the code used to generate the model outputs. The segment anthropometrics for the upper body was then developed. An anthropometric table was created for: segment mass, center of mass, transverse radius of gyration, and longitudinal radius of gyration. The upper body percentage of body mass was divided into mass for each of the lumbar vertebra segments, i.e., the total mass weight divided by 7 equals the approximate mass for L5 and the other 6 segments. The seven sections in this model are L1 to L5 plus T11 and T12.

Mass is concentrated into a cylindrical shape for segments; thus, each lumbar section segment was modeled as short cylinders. Whereas a longer segment, such as the femur, would be a long cylinder segment. The center of mass and moment of gyration for the lumbar are at the origin of each vertebrae. Once all the segments are defined, the hierarchy of the elements is defined in the model. The development of a hierarchy is necessary so Nexus can process the segments kinetics. Typically, there is one root segment and the other segments connecting to that root segment are the child segment. The child segment is then re-classified as a parent segment if another segment links to it. The thorax was chosen as the root segment, since it met the criteria for having the most markers and the most segments linked to it. Because the lumbar section has seven segments, the T11 becomes the child to the thorax instead of the pelvis, then the T12 becomes the child to T11. This is repeated up to the sacrum, then the sacrum becomes the child to the pelvis and the linking continues to the feet. Now that the hierarchy is complete, the kinetic values for each segment can be found in the Nexus subject section model outputs, as is the segment angles. See Figure 11.

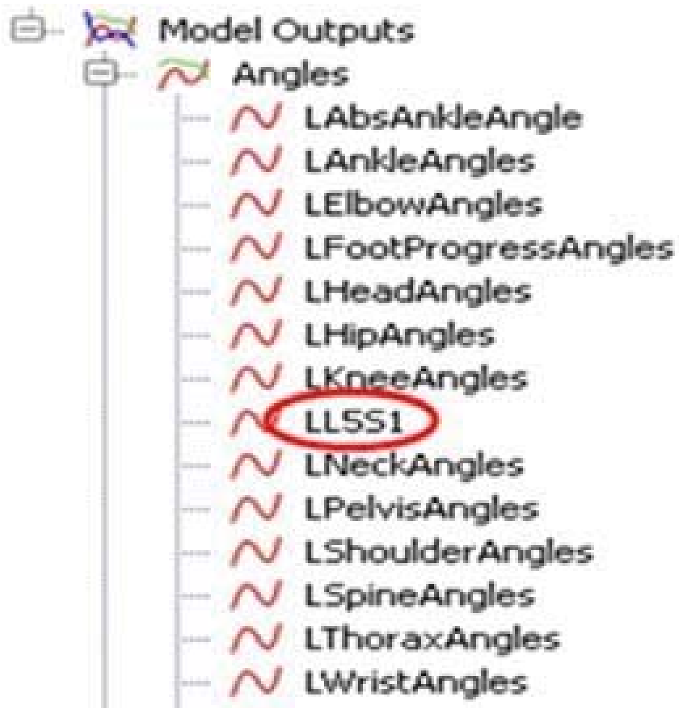

Figure 11. Model output of joint and L5/S1 angles

The following code in this section is not the complete S-Model BB code: however, a small section of the code is shown here to explain how the lumber spine section was included in the PIG model to generate L5/S1 outputs.

The S-Model begins by first duplicating the associated BB thorax (a) and pelvis (c) segments using the exact PIG marker terminology. This duplication serves as a reference point for the inclusion of the lumbar section of the S-Model. The S-Model is a combination of code reconstructing and defining a PIG thorax, a PIG pelvis the BB spine code. This S-Model is then mapped within the PIG-generated model in Nexus.

Once the PIG thorax and PIG pelvis are redefined in the Golem script, a T10 axis location (b) is added to the thorax, and a sacrum axis is added to the pelvis (d). Both axes are needed to serve as the end point variables for the Spine function. To establish the location of the center of the thoracic 10 vertebrae and the sacral vertebrae, the 50th percentile sagittal distance between the associated reflective markers, and center of the thoracic 10 vertebrae and sacral vertebrae, were estimated from (Robins and Reynolds, 1975), and the sacral vertebrae angle was estimated as the average male sacral angle of 40 degrees, taken from (Chaffin, 1969). Once the T10 and S1 axes are established, the Vicon BB Spine function is used to create the T11 to L5 vertebrae (e). The default Spine function value of "one" was used for stiffness at both ends of the lumbar spine. The full S-Model includes all the code used to generate the complete hierarchy for the body segment, the angles, the forces, the moments, and the outputs for all of the lumbar vertebrae. The S-Model is available to the community within the Vicon Library.

(a) Defines the thorax segment

```
UThorax = (C7+CLAV)/2

LThorax = (T10+STRN)/2

FThorax = (CLAV+STRN)/2

BThorax = (C7+T10)/2

TRX0 = CLAV+0.125*(C7-CLAV)

Thorax = [TRX0,LThorax-UThorax,BThorax-FThorax,zyx]
```

(b) Create the T10 axis location

```
T10C = T10 + {TC,0,0}*Attitude(Thorax)

Thoracic10=[T10C,T10C-C7,T10C-CLAV,zyx]

Thoracic10Size = ThoraxSize/2
```

(c) Define the pelvis segment

```
PELF = (LASI+RASI)/2
```

Pelvis = [PELF,LASI-RASI,PELF-SACR,yzx]

Pelvis = (LHJC+RHJC)/2 + Attitude(Pelvis)

(d) Create a sacrum axis

SACRC = SACR + {SC,0,0}*Attitude(Pelvis)

Sacrum=[SACRC,LPSI-RPSI,LASI-RPSI,yzx]

SacrumSize = PelvisSize/2

(e) Spine function to create the virtual T11 to L5 vertebrae. The T11 to L4 code is similar to the L5 code shown below.

SPINE(Sacrum,L5,L4,L3,L2,L1,T12,T11,Thoracic10,1,1)

L5_1={-22,0,15}*L5

L5_2={15,15,15}*L5

L5_3={15,-15,15}*L5

L5_4={-22,0,0}*L5

L5_5={15,15,0}*L5

L5_6={15,-15,0}*L5

As seen in Figures 12, 13, and 14, the difference in shape of the lumbar spine and the movement of its lumbar vertebrae segments changes accordingly during the ROM activity.

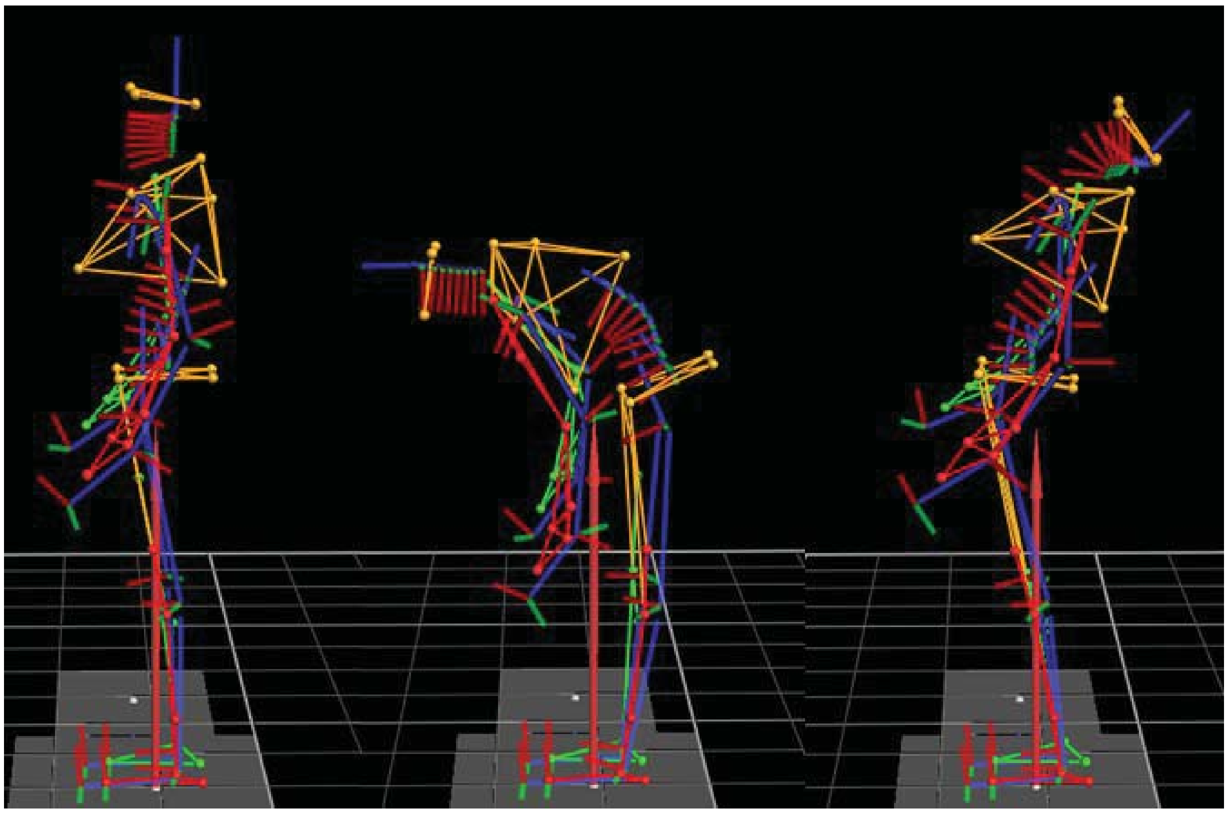

Figure 12. Forward flexion backward extension

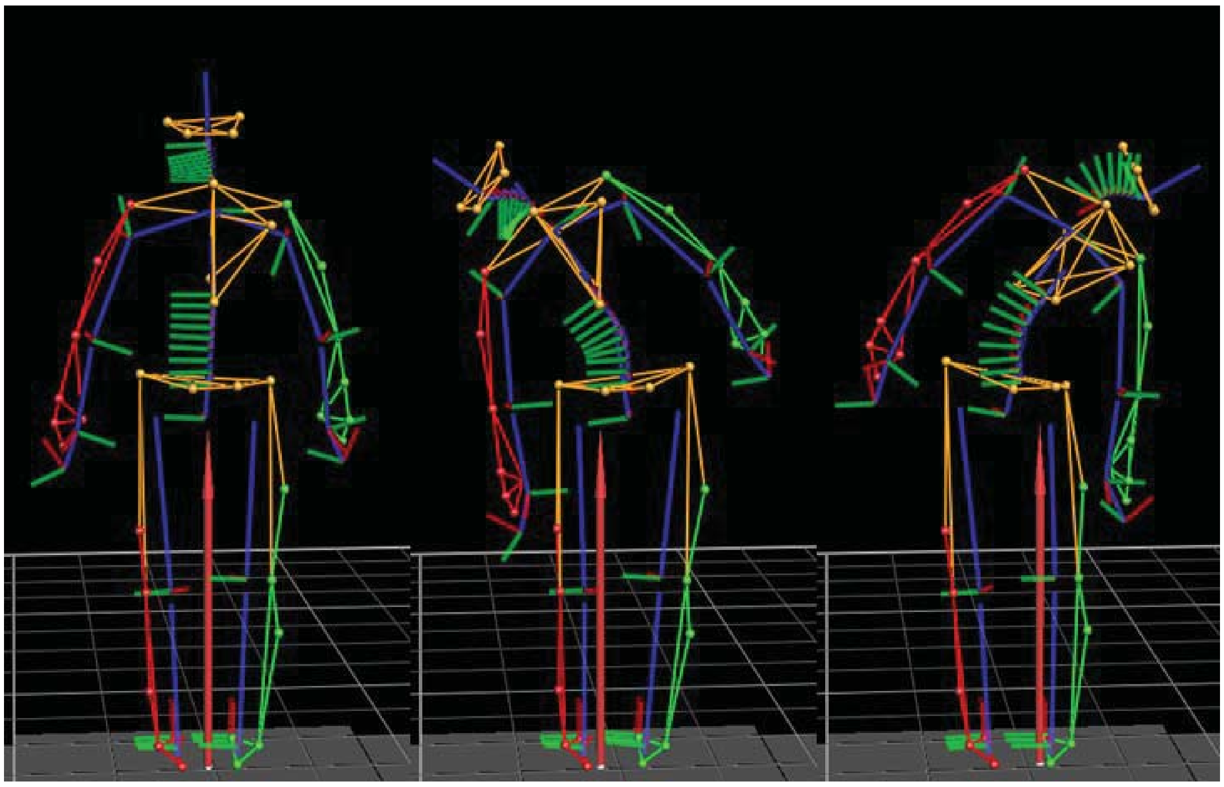

Figure 13. Left and right tilting

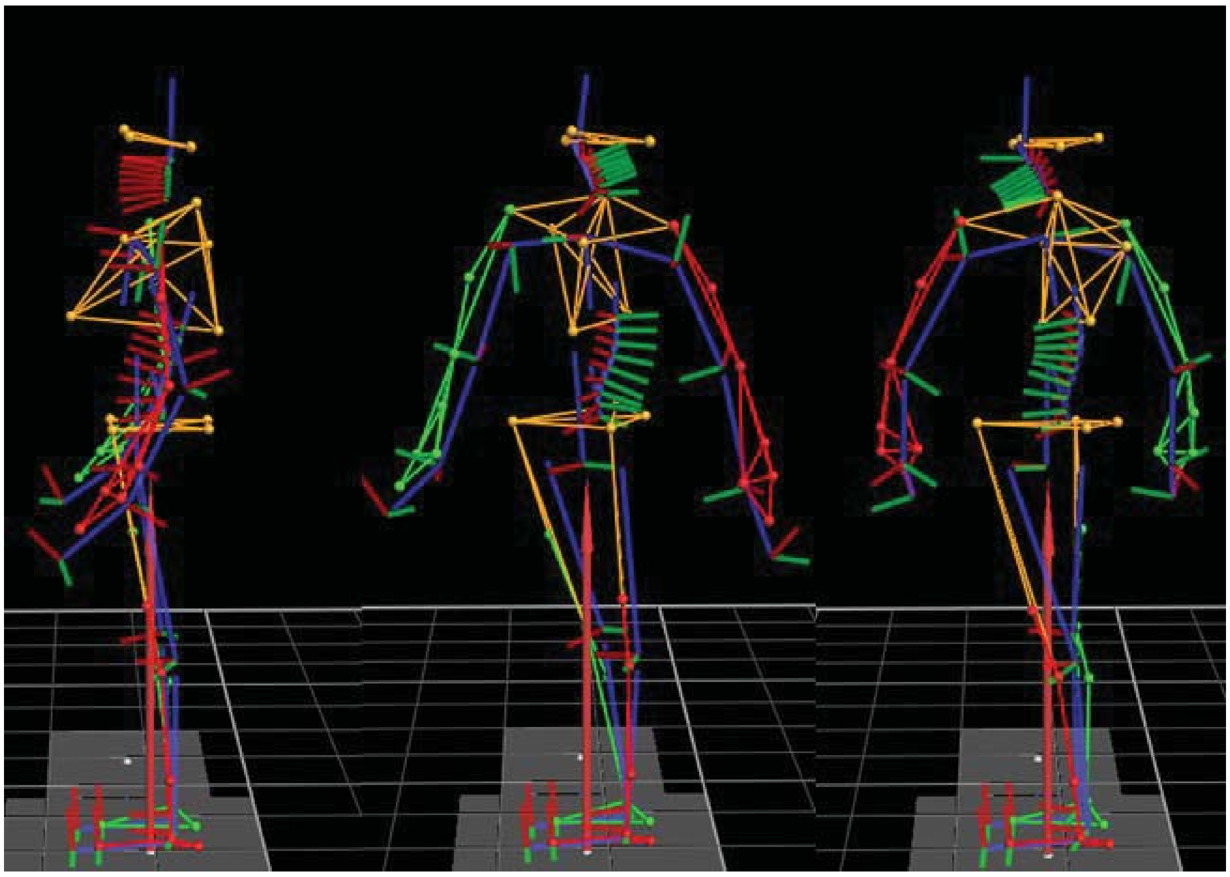

Figure 14. Left and right twisting

The next phase of development for the model would have been to include muscles to generate the internal muscle kinetics; however, because at this time the AB GaitFullModel was available, it was decided to use the AB modeling instead of continuing to include muscles into the S-Model. This S-Model was used for generating vertebrae angles that was used in another model for modeling the axial compression, shear, and bending moments for selected Olympic lifts. (Eltoukhy et al., 2016)

AnyBody Technology

The AB software and modeling program were chosen because they allow for detailed bones and muscles, and they use optimization to calculate the L5/S1 kinetics. The open source generic AB validated GaitFullModel model was chosen because it is freely available, and the programming code can be altered so there is no need to develop and validate a new model from scratch.

Over the last 10 years, the AB modeling system, which uses optimization to determine the muscle activities for all muscles in the human model, and the open-source human models have evolved from the lower extremity GaitUniMiami model (Eltoukhy & Asfour, 2010; Asfour & Eltoukhy, 2011) to the full body generic GaitFullModel of the human. The generic GaitFullModel model is driven by motion capture and has detailed anthropometrics for the bones and muscles. The programing code is open source and is easily available for the community to modify to a specific human activity.

The trunk portion of the GaitFullModel was validated for several static lift postures by comparing the AB generated L4-L5 forces with the L4-L5 intradiscal pressure. There were several different static postures analyzed and within these comparisons two box heights were evaluated: one evaluation with the box at shoulder height and the other evaluation with the box at thigh height, which is at similar height as this Placement Control study. Using the same anthropometrics from the Wilke study (Wilke et al., 1999), and converting the intradiscal pressure to forces using the MRI measured L4-L5 disc area, the biomechanical model resulted in an L4-L5 axial force in comparison to the intradiscal pressure (de Zee et al., 2007). In 2008, the AB GaitFullModel was applied and validated for a wheelchair activity (Dubowsky et al., 2008). More recently, the GaitFullModel was compared with 6 biomechanical tools (Rajaee et al., 2015). The AB model and the regression models (Arjmand et al., 2012) predicted L4-L5 intradiscal pressure values that were in close agreement with the in vivo intradiscal pressure for several postures, which included a box being held at shoulder height and at waist height as is being studied in this Placement Control study. The dynamic motion of the human is typically recorded using motion capture systems. Motion capture coupled with the biomechanical model ensures a realistic movement of body joints and is capable of estimating spinal segments' kinematics and loads (Eltoukhy et al., 2015).

A more recent study compared six biomechanical tools used for estimating spinal forces (Rajaee et al., 2015). The AB model and the regression models (Arjmand et al., 2012) predicted L4-L5 intradiscal pressure values were in close agreement with the in vivo intradiscal pressure for several postures, which included a box being held at shoulder height and at waist height as being performed.

Development of the Box Lifting Model

The Box Lifting Model was developed by modifying the generic GaitFullModel programming code provided by the AB library. Within this model there are several programming files for defining the human body, bones, muscles, and anthropometrics. These files are executed through the main programming file. To develop the Box Lifting Model, most of the programming was done in this main programming file. This additional programming code generated the box in the model and established the box mass, orientation, location, size, inertia, and linked kinetic reaction connections from the box to the hands. The motion capture markers were also defined exactly in the programming code as they were defined during the motion capture, including the markers on the human per the Vicon PIG setup (Stambolian et al., 2014b) and the markers defining the box. The model first runs a motion and parameter optimization, which optimizes the markers' locations and the bone sizes based on the subject's height and weight. For the motion and parameter optimization to run properly, the initial human posture in the Box Lifting Model needs to be adjusted in close proximity with the initial human posture of the motion capture for the first frame of the motion capture sequence. This requires adjusting the skeleton for the initial conditions according to each subject's initial joint angles, which is time consuming. Therefore, a process was developed by adding a code to the Box Lifting Model to approximate the initial human posture. This approximation is used to set the Box Lifting Model's initial human posture. Once the motion and parameter optimization is completed, the model is run a second time for the inverse dynamic analysis sequence, which adds the muscles into the model and then establishes the internally generated kinetics for each time step of the motion. During this second run of the model, the reaction forces for the joints and the muscle activities are created and can be visualized in a graph as part of the AB software. Code was also developed in the main programming file to create and export a text file that includes the predefined required data, such as the joint reaction force or muscle activity. To date, there has not been a motion capture-driven dynamic Box Lifting Model developed and validated using the AB modeling system. The development and validation of the Box Lifting Model was done to evaluate the lower back L5/S1 stresses. For a dynamic lifting activity, optimization is used to establish the muscle forces to the joints through the AB modeling system and motion capture.

Experimental setup

The sagittal-plane lifting setup with the box and shelf directly in front of the subject included a shelf height at 50”, a shelf at 30”, and a box weighing 30 pounds (Stambolian et al., 2011). Each subject was instructed to walk onto the force plates and then lift a box from the ground up to a shelf. The box was in front of the subject's feet, and the shelf was in front of the box; there was no twisting involved in the lift. The subjects were instructed to: (1) place feet on the force plates, and (2) lift and place the box evenly with the edge of the shelf. Placing the box evenly to the edge of the shelf promoted the careful placement of the box by requiring the subject to slowly place the box edge coincident with the shelf edge. Reflective markers were used to record the three-dimensional location of the box relative to the shelf to ensure that the start and stop locations between subjects were consistent. Reflective markers were placed on the subject using the Vicon PIG marker configuration. For each subject, the Vicon data file generated during the lift, which contains the subject's three-dimensional kinematics, was imported into the AB optimization software. The AB modeling software used a polynomial solver with power three, a dynamic optimization methodology, to determine the trunk muscle activities (Rasmussen et al., 2001).

Figure 15 shows the experimental set-up and the corresponding AB post-optimization model for the same lifting exercise. As shown, the subject is standing with each foot on one force plate, and the box has been lifted to the 50” shelf. The adjustable shelf design allowed the shelf table to be lowered to a 30” height. Also, the reflective motion capture markers are seen on the subject and on the Box Lifting Model from the posterior view of the subject.

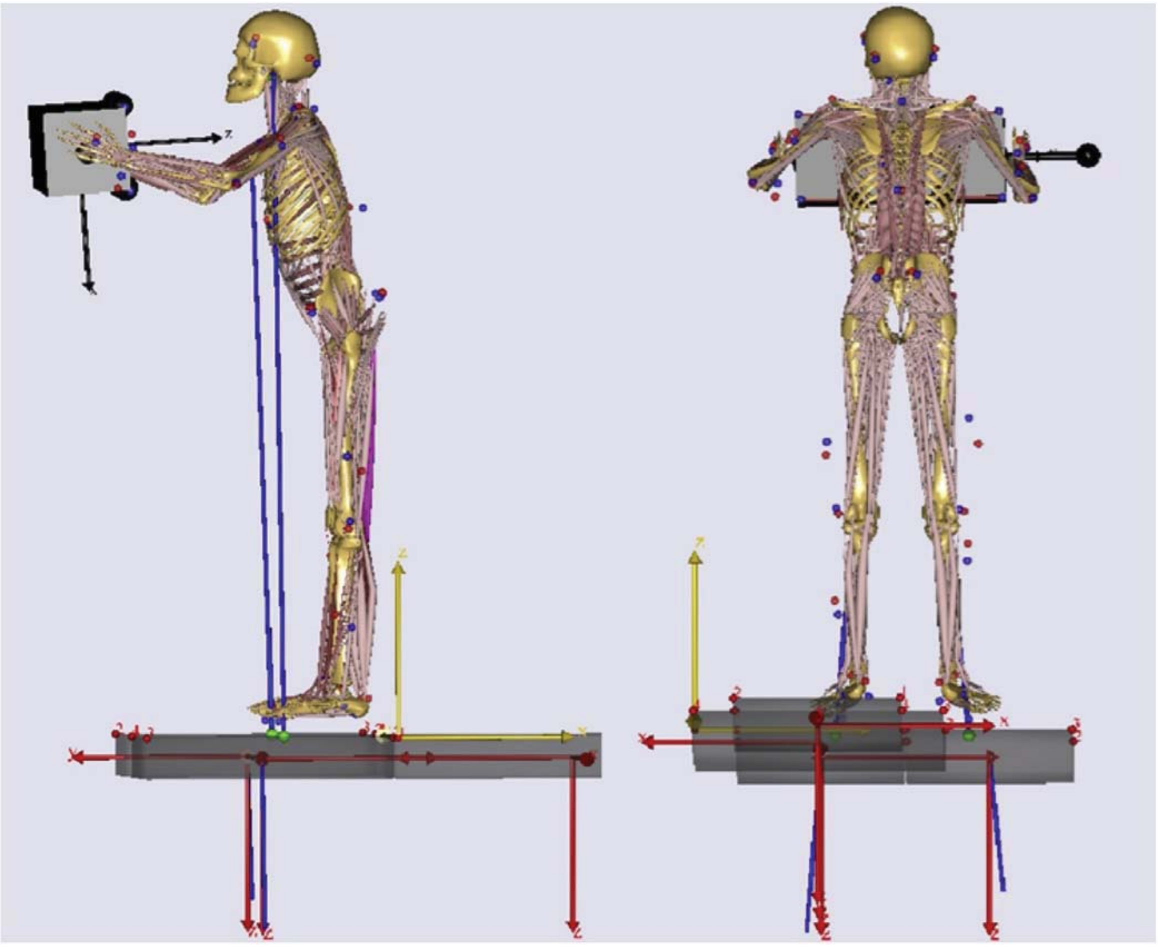

Figure 15. University of Miami Box Lifting Model

Experiment procedures

There were seven subjects used for the validation. The subject's height and weight are shown in Table 14.

Table 14. Subject height and weight

Subject	Height in inches (Cm)	Weight in pounds (Kg)
1	176.0	76.0
2	182.8	93.6
3	177.0	62.7
4	177.0	83.8
5	170.0	83.3
6	190.7	93.1
7	176.5	74.7
Mean	178.6	81.0
SD	6.5	10.9

For each subject, the locations of the EMG electrodes were determined, and the electrode area was shaved to remove any hair; fine sand paper was used to remove dead skin; and, cleanser was used to remove all residues. EMG electrodes were placed on the subject's left and right erector spinae (ES) 3 cm lateral to L3 spinous process, external obliques (EO) approximately 15 cm lateral to the umbilicus, internal obliques (IO) below the external oblique electrodes and just superior to the inguinal ligament, and rectus abdominis (RA) 3 cm lateral to the umbilicus (McGill, 1992). Figure 16 depicts the locations of motion capture reflective markers and the approximate locations of the EMG electrodes in relation to the muscles in the Box Lifting Model.

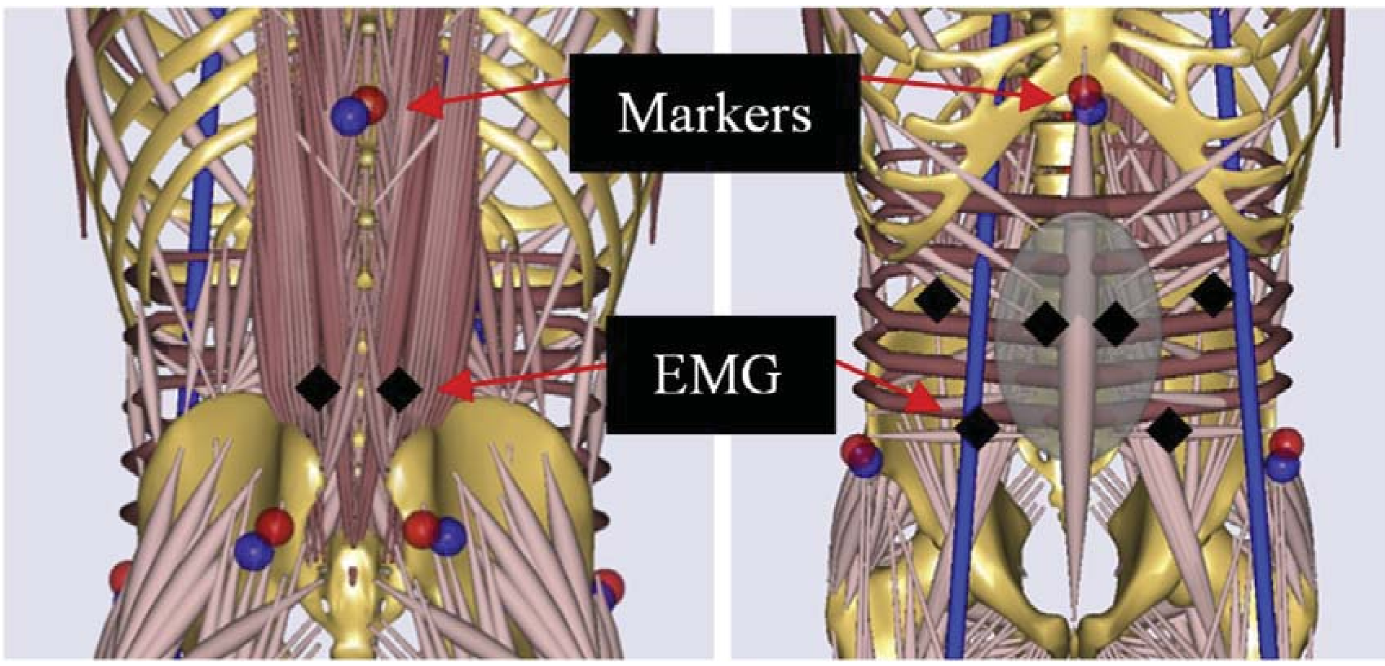

Figure 16. EMG electrode locations

For each of these muscles, the subject performed Maximal Voluntary Contractions (MVC) per (Konrad, 2005). The subject first performed the MVC exercise for the ES in a prone position with resistance provided during the contractions. The RA, EO, and IO electrodes were then placed on the subject. Next the subject performed the MVC exercise for the RA, EO and IO muscles. The subject lay on a platform with the knees bent and feet restrained. During the RA's MVC sagittal exercise, the trunk angle was approximately 30 degrees. During the Right EO's and Left IO's MVC, the subject aimed his right arm towards the left knee, and for the left EO's and right IO's, the subject aimed his left arm towards the right knee.

The reflective markers were then placed on the subject according to the Vicon Plug-In-Gait marker configuration. The subject was instructed to step with each foot within the corresponding force plate and then proceed to place the box as carefully as possible so the outside edge of the box aligned with the outside edge of the 50” shelf space. Following that, the subject performed two practice lifts, and began the experimental lifts of placing the 30-pound box on the 50” shelf space. The same lifting and placement procedure was followed for the 30” shelf. The lifts performed by the subjects were continuous and started from the floor and ended at the shelf . To evaluate the careful placement portion of the lift, only a segment of the full lift motion capture was used in the analysis. This portion of the motion capture started when the box began to enter the shelf and ended when the box was carefully placed on the shelf as seen in Figure 17.

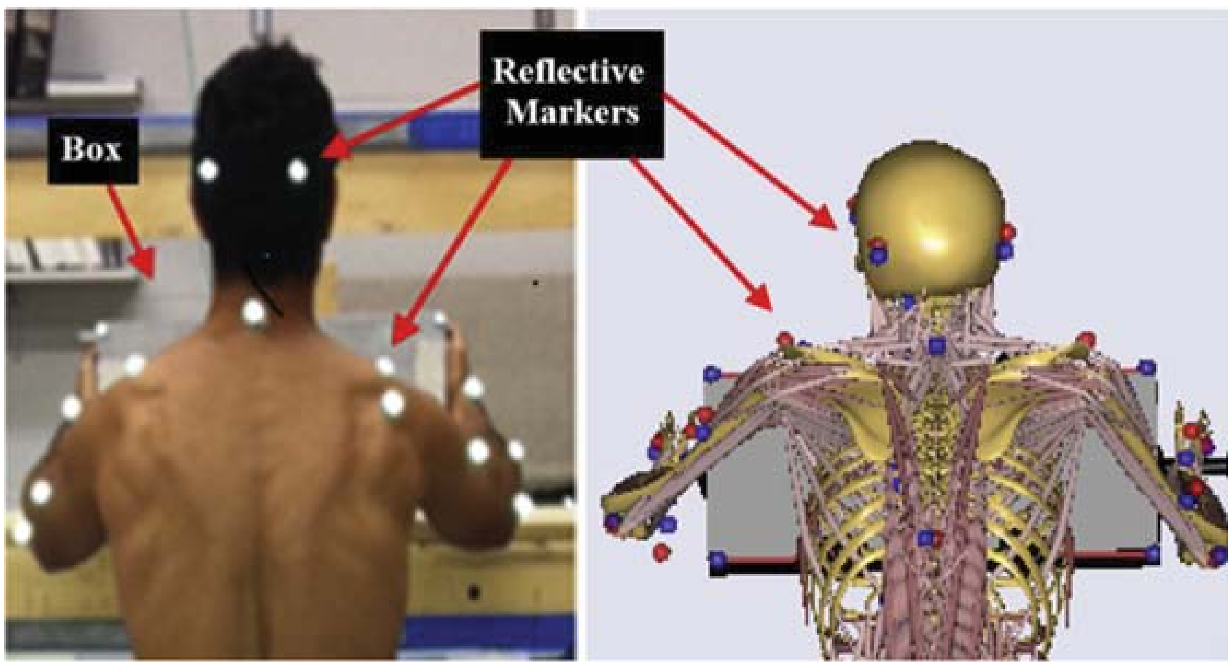

Figure 17. Box carefully placed on the shelf

Box Lifting Model verification and validation

The Box Lifting Model verification and validation is comprised of four phases: (1) The first phase is a literature review to show evidence that the generic GaitFullModel is valid prior to including the programming code for adding the box to the model to create the Box Lifting Model. Since the generic GaitFullModel was previously shown to be valid, the Box Lifting Model should also be valid if the additional programming code developed in the Box Lifting Model is correct. (2) The second phase is to verify that the new code developed in the Box Lifting Model is correct by comparing the reaction forces on the lower back based only on the weight of the box. If the forces on the lower back increase as the box weight increases, then the new code developed in the Box Lifting Model is correct. (3) The third phase is a verification by comparing the human EMG muscle activity to the Box Lifting Model's simulated muscle activity. It is accepted to compare EMG activity of the subject's muscles to the estimated muscle activity derived using optimization (Hughes et al., 1994; McMulkin, 1996; Thaxton, 2009). Therefore, this verification is to show evidence that the Box Lifting Model's muscles acting on the lower back and stomach are adequately representing the human muscles. For example, when lifting a box in the sagittal plane, the lower back muscles should be more active than the stomach muscles because the lower back muscles are working harder to hold the box up, whereas the stomach muscles are used only to help balance the torso. (4) The fourth phase is a validation of the model was accomplished by applying the Box Lifting Model to evaluate a box lifting activity placing a box on a 30” shelf and a 50” shelf.

Comparison of L5-S1 reactions to the lifted box weight

This analysis started with the motion capture of the subjects lifting the 30-pound box and was run in the Box Lifting Model to generate the L5-S1 reactions for the 30-pound box weight. The box weight in the model code was then adjusted and run for a 15-pound box, and then again for a 45-pound box to generate the L5-S1 reactions for the 15-pound and 45-pound box weight. To ensure that the box weight was the only influence in this comparison, the body motions for the 15-pound and 45-pound L5-S1 reaction calculations were exactly the same as the body motions that took place with the 30-pound box; only the box weight value for the 15-pound and 45-pound box was numerically adjusted in the model. This was done for the 50" shelf and for the 30" shelf for all seven subjects. The L5-S1 reaction forces were averaged. As shown in Figure 18.

The proximal distal force and the anterior posterior force all increased as the box weight increased, which for a sagittal lift the proximal distal force and the anterior posterior force are the major contributors to L5-S1 forces. With the medial lateral force, only subjects 2 and 6 at the 50" shelf differed and showed a decrease in L5-S1 reactive forces instead of an increase. This discrepancy occurred with only 2 out of 42 trials performed.

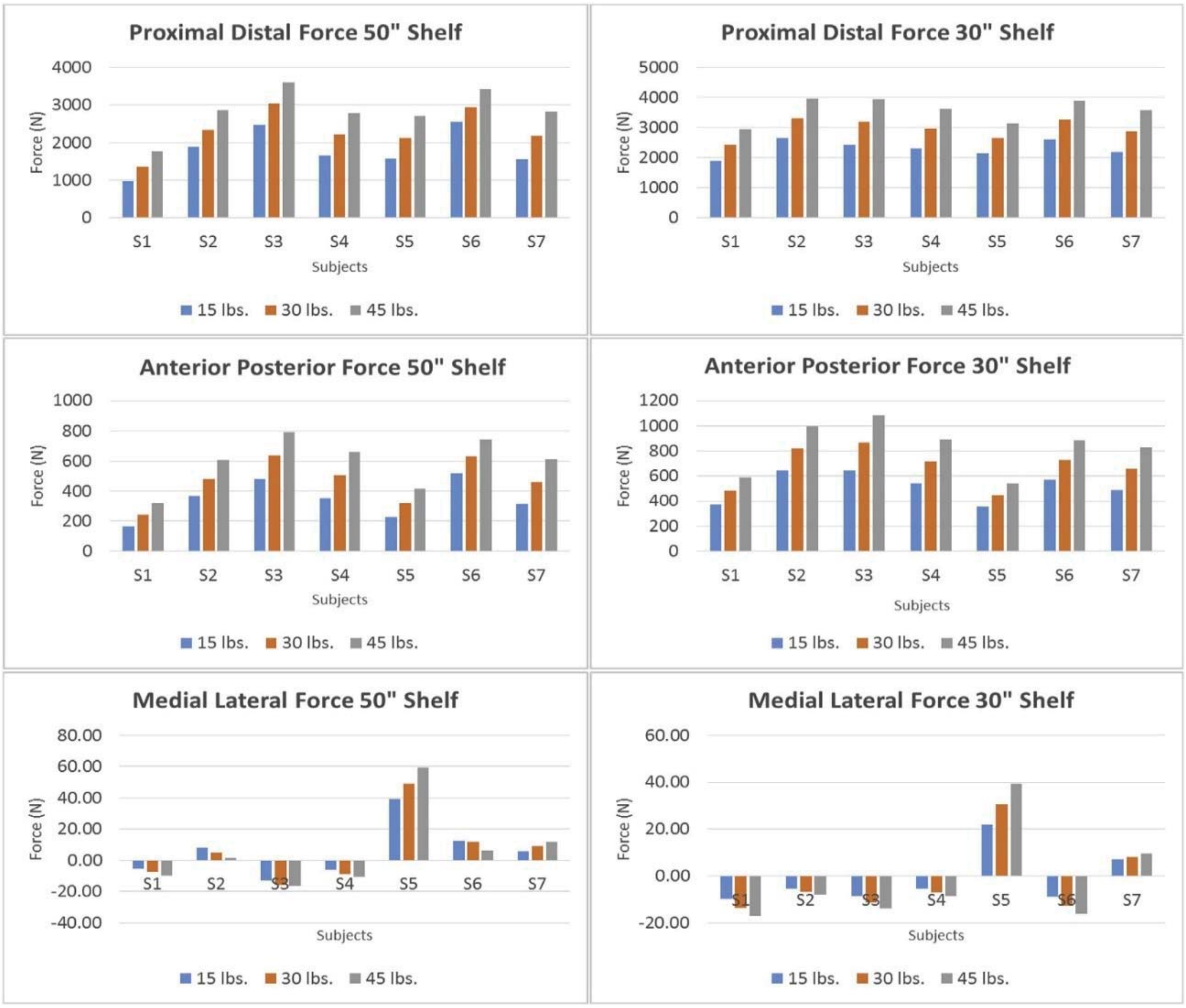

Figure 18. Comparison of L5-S1 reactions to increases of box weight

Relative comparison of EMG to predicted Anybody muscle activity

For each subject, the weight and height were entered into the Box Lifting Model programming code. By importing the Vicon data file, each subject's lift specific motion capture data, along with the synchronized force plate activity, were included in the AB Box Lifting Model programming routine. The optimization routine in the AB software generated the predicted muscle activities, and EMG was used to determine the actual muscle activity. For each muscle, the average of the Box Lifting Model predicted muscle activity were calculated. The EMG muscle activity is normalized EMG, and the AB muscle activity is AB muscle force divided by AB muscle strength. Therefore, the mathematical definition of AB simulated muscle activity is not numerically the same as the EMG muscle activation; hence, the AB muscle activity values will not be the same as the EMG muscle activity values.

The raw EMG data for the MVC and the muscle activities during the lifts were collected at 1800 Hz. These EMG trunk muscle activities for the MVC and lifting exercises for the left and right: ES, EO, RA, and IO, were processed using the MyoResearch XP software (Master Edition 1.07.41). The EMG signal processing included high-pass Butterworth Filter at 30 Hz, rectification, low-pass Butterworth Filter at 1000 Hz, and Smoothing RMS (60 Hz). For each lift, the amplitude normalization for each left and right muscle EMG activities was based on the MVC values, e.g., right rectus abdominis muscle activity during the lift was normalized with the right rectus absominis MVC muscle activity. This provided the subject specific percentage of muscle activity curve for each of the muscles per subject. For each muscle, the average of the EMG muscle activity was calculated.

For this type of sagittal lift without twisting, the back muscles would be expected to be more active than the stomach muscles, and is shown in the relative comparisons of EMG activity to the Box Lifting Model's muscle activity. This comparison was done for: both the left and right muscle groups, two shelf heights, and one box weight. As shown in Figure 19, the erector spinae back muscles were more active than the stomach muscles.

This is expected with a sagittal lifting activity. With each individual comparison of EMG and Box Lifting Model, the erector spinae is more active than the stomach muscles, and the rectus abdominis is the least active muscle, which is also expected. The external and internal oblique muscles are aiding in balancing the torso during the placement of the box. There was only one outlier. For the left 30” shelf, the external oblique EMG muscle activity for the third subject was more active than the erector spinae.

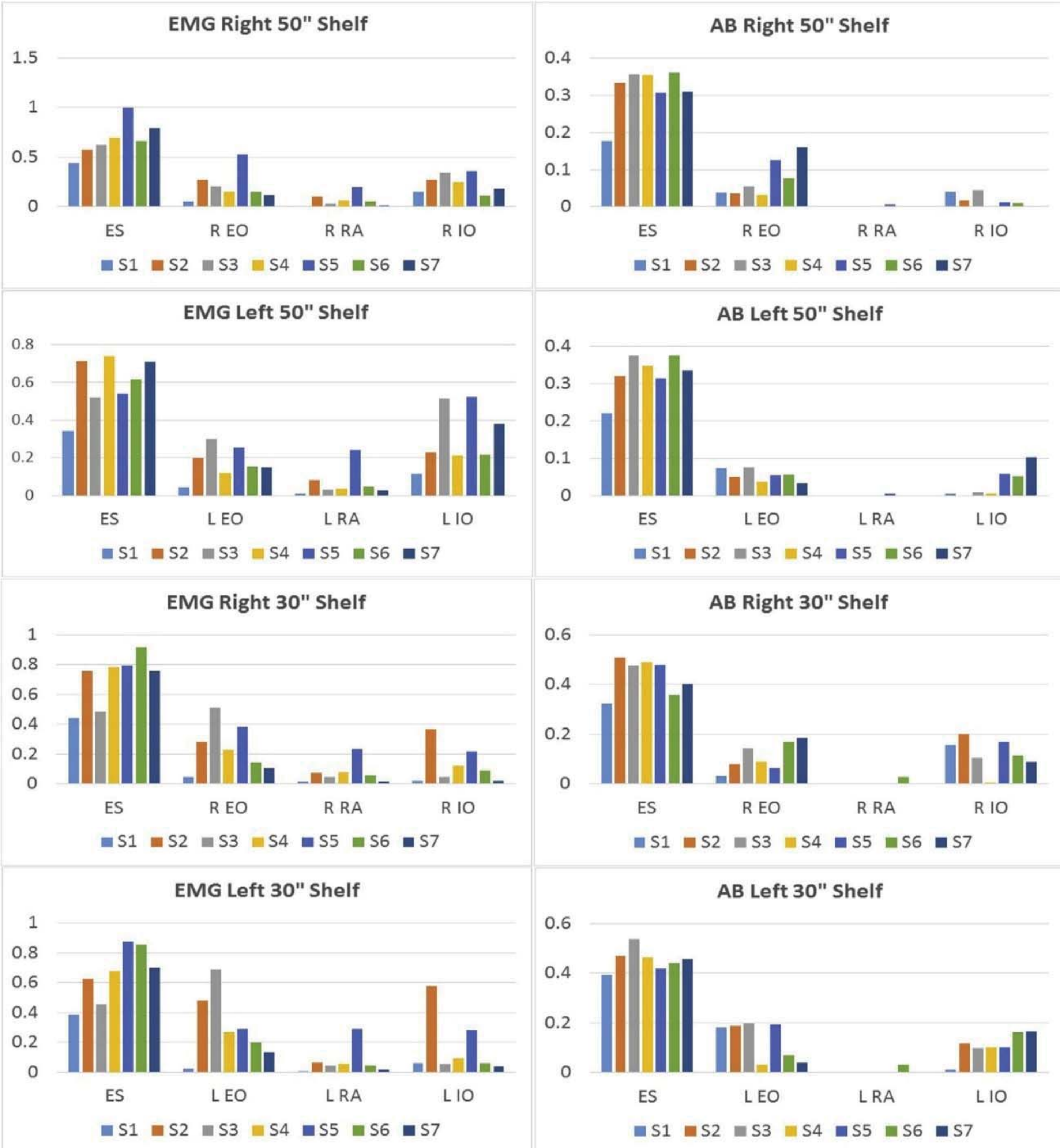

Figure 19. Relative comparison of EMG to AnyBody muscle activity

Muscle to muscle comparison of EMG to AB muscle activity

This muscle to muscle comparison was done between the AB predicted muscle activity and the EMG measured muscle activity, for the left and right muscles, for two shelf heights, and for one box weight. Since the major muscles reacting on the L5-S1 for a sagittal lift are the erector spine muscles, this comparison was done between the AB predicted muscle activity and the EMG measured muscle activity for these muscles. Following is the statistical analysis for this comparison. The linear correlation analysis was performed using the Palisade StatTools software Version 6. Table 15 provides the correlation values for the relationship between the predicted and measured values for the 30" shelf and the 50" shelf for both left and right muscles. These correlation values were assessed using the t-Test. At a 0.01 significance, the t-Test critical value is 2.575 for a support the claim that the AB predicated values linearly correlate two-sided t-distribution. There is sufficient sample evidence with the EMG measured values at a 0.01 level of significance.

Table 15. Correlation t-Test

Subject	30″ left		30″ right	
	Correlation	t-Test	Correlation	t-Test
1	0.663	13.053	0.623	11.956
2	0.642	11.089	0.675	11.941
3	0.522	7.630	0.467	6.729
4	0.674	13.178	0.659	12.762
5	0.790	12.407	0.837	14.391
6	0.403	5.083	0.520	6.724
7	0.643	13.248	0.565	11.190

Subject	50″ left		50″ right	
	Correlation	t-Test	Correlation	t-Test
1	0.464	7.063	0.265	3.943
2	0.814	18.591	0.867	22.448
3	0.779	12.432	0.802	13.305
4	0.777	15.730	0.825	18.164
5	0.604	7.261	0.580	6.888
6	0.875	21.094	0.784	15.379
7	0.688	14.412	0.682	14.214

Box Lifting Model applied to evaluate a box lifting activity

The Box Lifting Model was then applied to evaluate a box lifting activity on a 30” shelf and on a 50” shelf with the 30-pound box. As seen in Figure 20, with the two shelf heights, the higher 50” shelf height resulted in less stress to the L5-S1 proximal distal forces and anterior posterior forces. This agrees with previous findings where an increase in lifting height is associated with a decrease to the load on the lower back (Hoozemans et al., 2008).

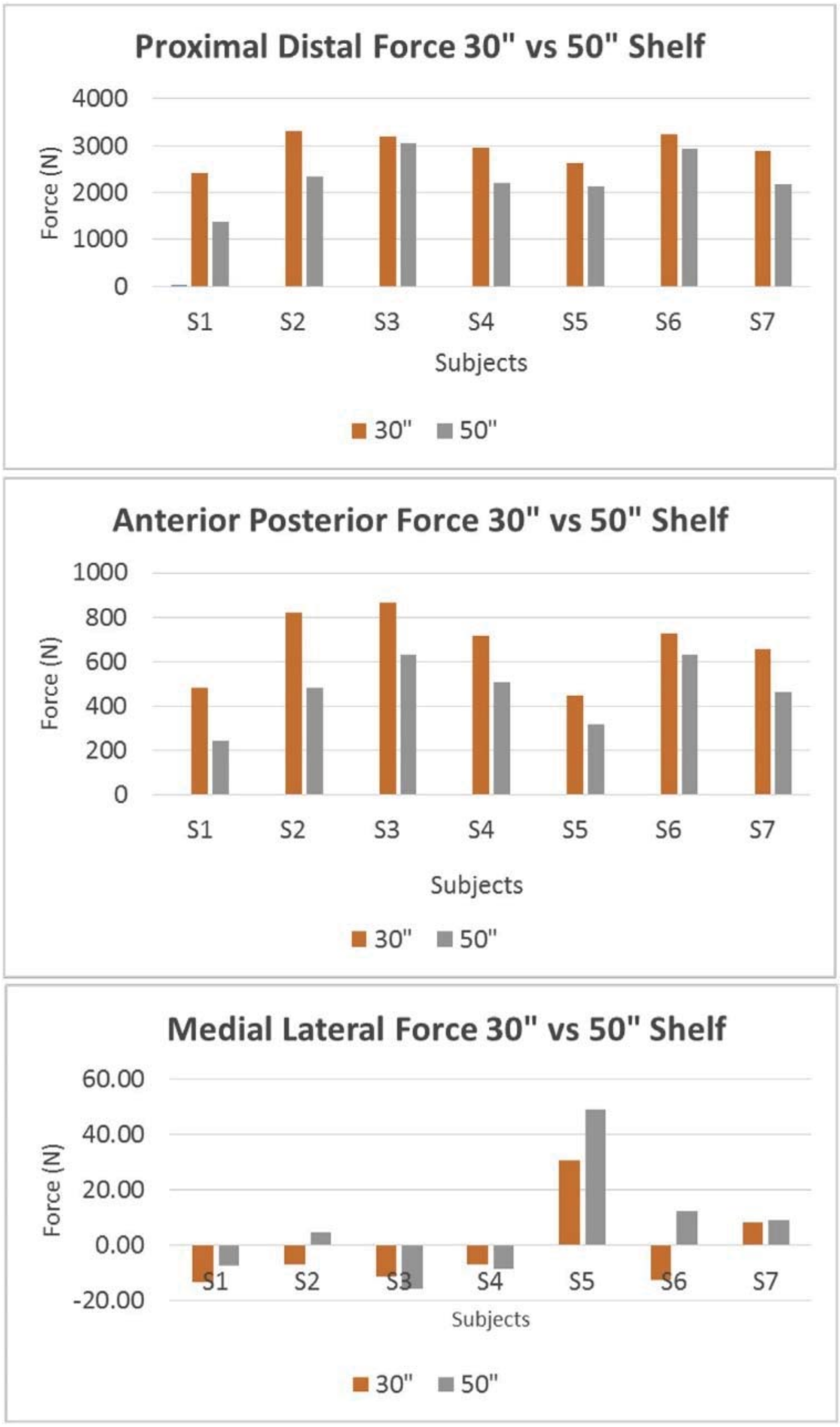

Figure 20. Force comparison with two shelf heights.

The University of Miami Box Lifting Model is now ready to be used to generate kinetic L5/S1 forces from the experimental data for the Placement Control study in this dissertation.

CHAPTER 4 METHODS

Experimental set up

The experimental factors studied included box weight, shelf height, and shelf space. The box weight had three levels: 15, 30, and 45 pounds, and shelf height had two levels: 30" and 50". The shelf space was either restricted or unrestricted (open), as explained in the avionics shelf and boxes section. To maintain good configuration management, a code was developed. The first number was the type of lift configuration; a double underscore indicated it was the second unique lift. The next number was the subject's number. The next number was the sequence for the random number picked for this lift (1 to 24). The next set of numbers were the lift configuration, the weight of the box, the shelf height, and restricted or unrestricted shelf space. Then -2 was if it was the second (repeated) lift. For example, 5__33_18_30-30-UR-2

University of Miami Biomechanics Laboratory

Kinematic data were captured and recorded at the University of Miami's Biomechanics laboratory with the Vicon (Oxford Metrics, United Kingdom) Nexus software version 1.6.1.57351 and 10 MX cameras providing 1024 x 1024 pixel resolution sampled at a rate of 120 Hz. Force data were collected with Kistler force plates (Model: 9253B, sampling rate: 2400 Hz). EMG was collected with a Noraxon Telemyo System (Noraxon USA., Inc., Scottsdale, Arizona). The Noraxon Telemyo System is synchronized and integrated into the Vicon Nexus system (Eltoukhy et al., 2010). See Figure 21 showing the University of Miami Biomechanics Laboratory. The EMG data from the "Validation lifts" were used for validation of the Box Lifting Model. The motion capture data from the “Random box lifts” were used in the Box Lifting Model to generate the L5/S1 proximal/distal and anterior posterior force data for the analysis.

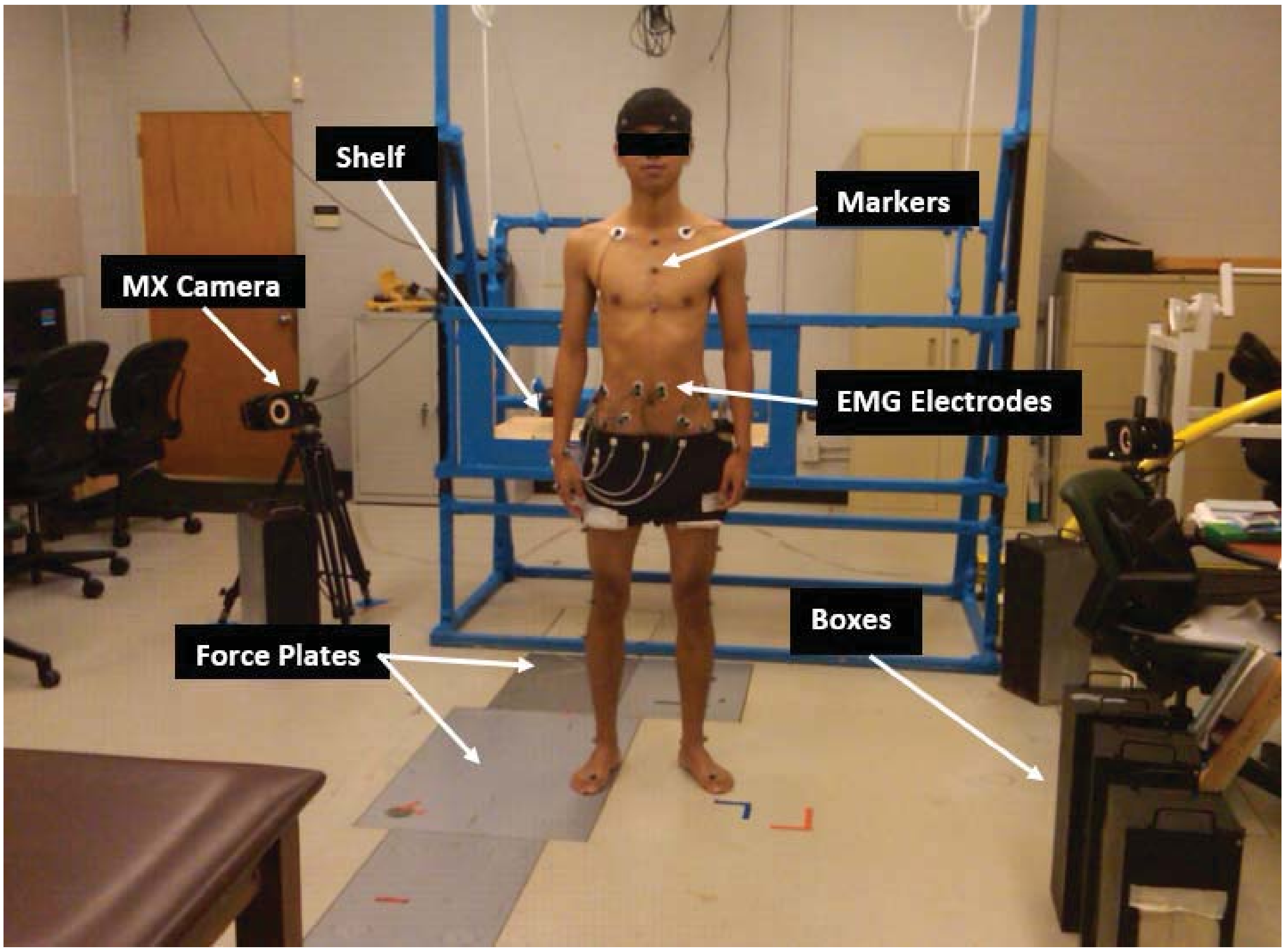

Figure 21. University of Miami's Biomechanics Laboratory

Subject selection and experimental criteria

Subjects used for this study included twenty male college students with no prior training for installing avionics boxes. The subjects’ mean weight was 71.4 kg with a Standard Deviation (SD) of 8.7 kg, and the mean height was 1730.6 mm with a SD of 69.1 mm. Each subject was informed individually on the day of their experiment about the purpose of the study and the activities which they would perform during the study. The subjects signed the Human Subjects Informed Consent Form. The subjects were instructed where to stand, to bend their knees to pick up the box from the floor (so as not to use their back to avoid injury), to step forward with the right foot first then with the left foot (this was because of the force plate arrangement), and place the box as accurately and carefully as possible on the outline on the shelf. The subject performed one lift to ensure he understood where to stand, how to pick up the box, and how to place the box on the shelf. EMG electrodes were placed on the subject's lower back, and the lower back EMG maximum voluntary contractions were performed. The cables were removed from the lower back with the lower back electrodes remaining in place, and then the abdomen area electrodes were placed on the subject. The abdomen area maximum voluntary contractions were performed. The lower back was performed first, because there are fewer EMG electrodes touching the table when they roll over to perform the abdomen MVC. Figure 22.

Figure 22. Maximum voluntary contraction

Reflective markers were then placed on the subject using the Vicon PIG marker configuration. Then the experimental random box lifts began. The different randomized configurations were a combination of box weight, shelf height, and shelf space, (See Appendix for test plan). Twelve different lifts were performed twice equaling 24 lifts. All 24 lifts were randomized differently for each of the 20 subjects. Each random lift has a unique identifier for configuration management of the 480 total lifts. The first number is box weight, the second number is shelf height, the third letter(s) is for restricted or unrestricted, and the -2 is for the repeat of the same lift. There was no training prior to the lifts, only short instruction. Figure 23 shows the randomized box lifts, including the post experiment validation lifts to be used for model validation. See Appendix for the lab test plan.

Check complete	Random Box Lifts	Notes
	45-50-R-2	
	45-30-R	
	30-30-R-2	
	30-50-UR	
	15-50-UR	
	15-30-R-2	
	30-30-UR	
	30-50-R-2	
	15-50-R	
	30-30-UR-2	
	15-30-UR	
	45-30-UR	
	45-30-UR-2	
	15-50-UR-2	
	30-30-R	
	15-30-UR-2	
	30-50-UR-2	
	45-50-UR	
	45-30-R-2	
	15-30-R	
	15-50-R-2	
	30-50-R	
	45-50-R	
	45-50-UR-2	

	Model Validation	Notes
	15-30	
	15-30_2	
	30-30	
	30-30_2	
	15-50	
	15_50_2	
	30-50	
	30-50_2	

Figure 23. Randomized lift procedure

The random box placements and the model validation placements were performed on the simulated avionics shelf constructed with easily adjustable shelf height between 30" to 50", using a pulley and counter weight, similar to how an elevator works. See Figure 24. As each lift was being set up in Vicon Nexus, the CM identifier was typed for each unique trail.

Figure 24. Shelf at 30" and 50"

After the subject performed the 24experimental lifts, they performed a set of lifts to be used for EMG validation of the Box Lifting Model. During these lifts, the subject did not step forward; they lifted the box and placed it carefully on the shelf. See Figure 25. There were four lifts performed twice which for the 20 subjects was a total of 160 lifts.

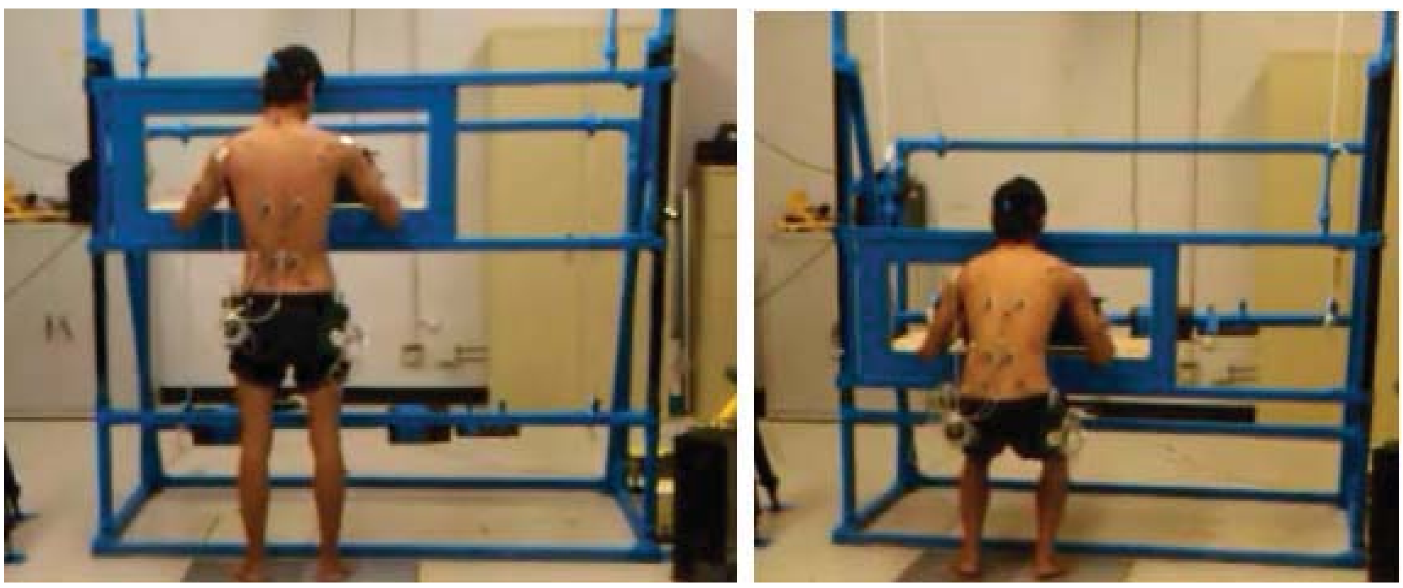

Figure 25. Validation lifts

Avionics shelf and boxes

Prior to the lift activity, the subject posed in a T-position with the arms at start and end of the lift; this was to make labeling easier in Vicon. The lift activity began by the subject grasping the box at the taped location, and lifting the box from the floor. See Figure 26. The tape was used to help with the grip and for consistent hand placement at the center of the box. The subject then steps with the right foot first and then the left foot, because of the faceplate arrangement. As they moved forward and as the box went into the shelf, they would place the box as accurately and carefully as they could on the shelf.

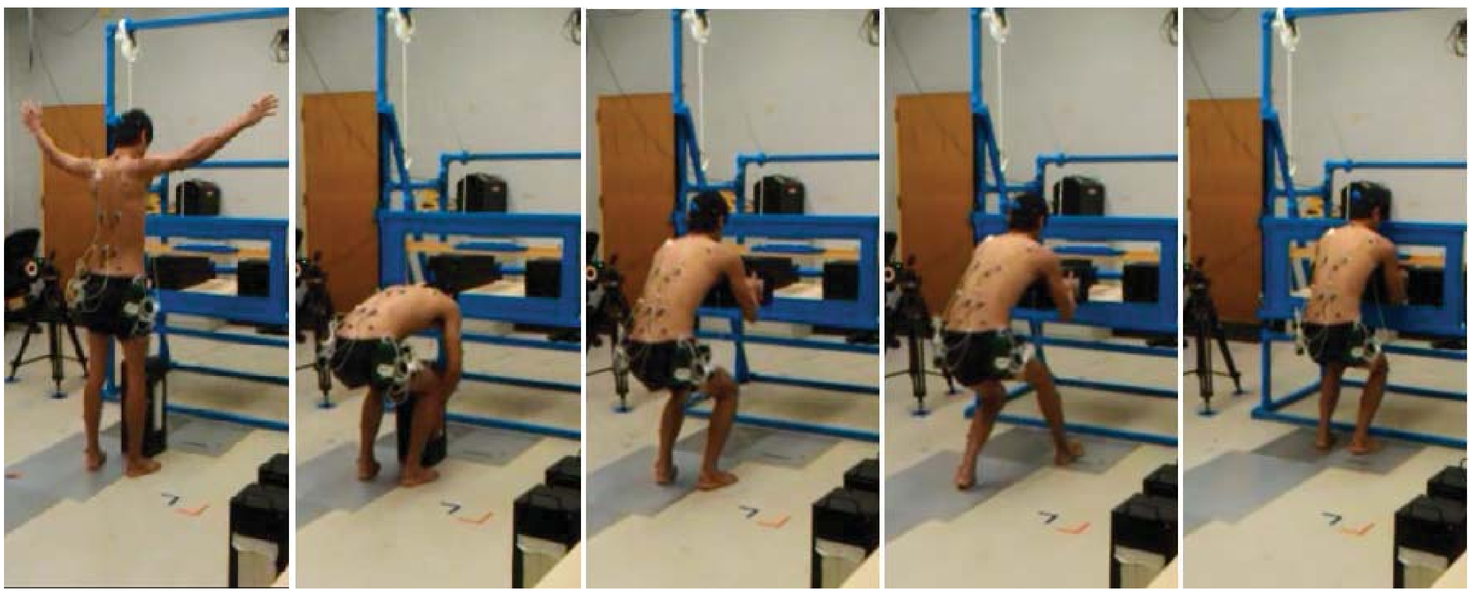

Figure 26. Complete lift activity with 30" shelf height

The analysis focus was on the box as it first enters the front shelf edge until each of the corners had reached the table. See Figure 27.

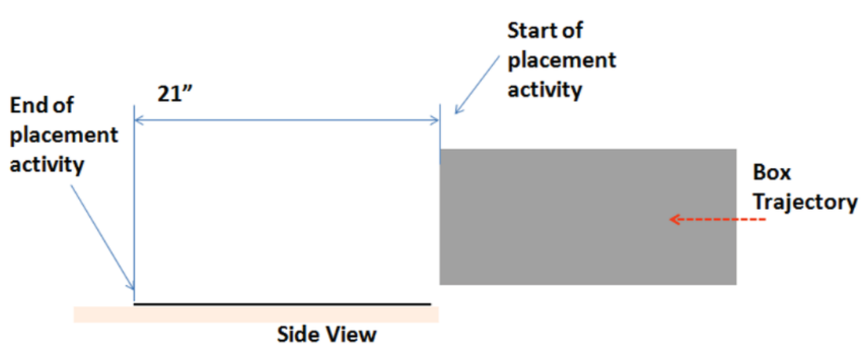

Figure 27. Box placement trajectory as the box approaches the target

Above the placement shelf there was a second removable upper shelf which replicated the restricted space above the box. There were two extra boxes on the shelf to simulate having a box to the left and right of the placement box. Markers were used to record the three-dimensional location of the box relative to the shelf to analyze the accuracy of placement. See Figure 28.

Figure 28. Mockup for avionics box and shelf (open, restricted)

Although the boxes in the space shuttle varied, in some cases very restrictive, the spaces between the boxes in the mockup had to be ergonomically friendly to the subjects. Making restrictions less than body size would not be safe for the subjects. Therefore, the clearances for the arms going between the boxes were determined using FAA HFDS Chapter 4 Design Equipment for Maintenance. Both arms would be reaching into the shelf, between two boxes, up to about the elbow. The FAA recommends 4.5" for elbow clearance when working in light clothing. This measurement was chosen for the distance between the placement box and the other two boxes, one to the left and one to the right. For the space between the box and upper shelf, the FAA recommends ½" around a box over 5" high when inserting a box with hands on the sides. Thus, there is a 1" clearance above the box. See Figure 28. The weight and size of the mock-up boxes were determined by using the dimensions from the space shuttle, previous lifting studies, and the ARNIC 404 Specification (1974). The metal portions of the table that were shiny were covered with blue masking tape, and the boxes were painted black, to eliminate reflections that would interfere with calibration of the motion capture cameras.

Subject strength measurements

Subject strength measurements were taken subsequently, using a force strain gauge. See Figure 29. The measurement was taken at 30" and 50" height with the same hand grip as was done with the random box placements for the experiment. See Figure 30.

Figure 29. Strain gauge

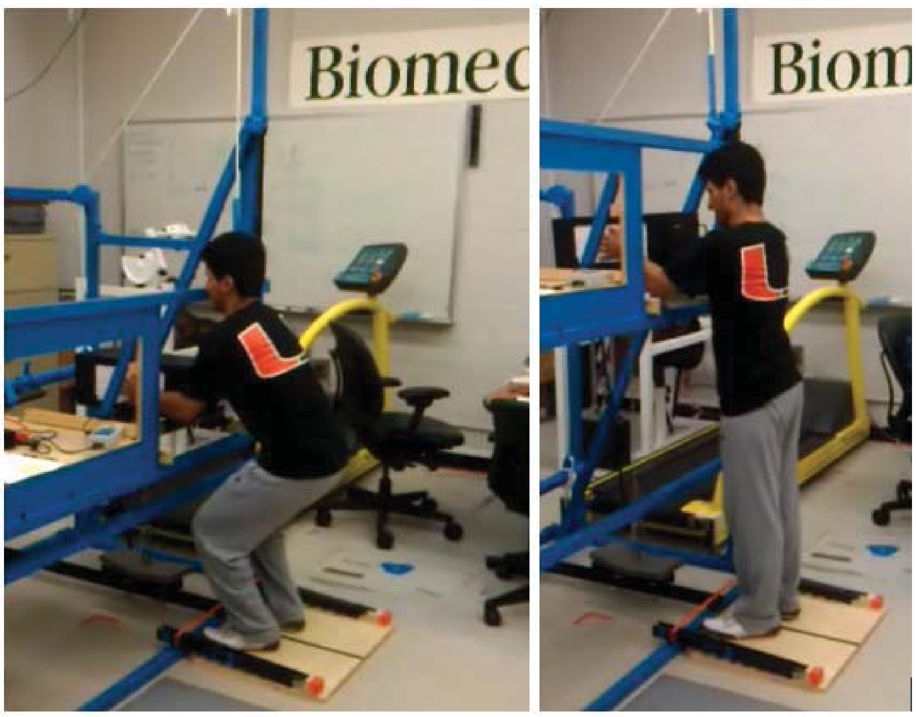

Figure 30. Subject at 30" and 50" strength set up

Placement Control definition

As defined in this research, controlled placement of the box is: (1) when the box lands accurately on the target, which is when the box final destination is on or close to the target; and, (2) when the box lands carefully on the target, which is when the box lands relatively flat and the time between corner landings is close where there are no corners skipping or scrapping as the box is making its way to the target on the shelf.

Hitting the front of the shelf by the box was not included in this definition because the experiment started once the box entered the shelf, and this type of error did not cause damage to the cold plate.

Accurate placement

Measurement of how accurate the box was placed on target was accomplished by reviewing the relation of the reflective markers on each corner of the box to the relative reflective marker placed on the shelf. The difference was measured between the box marker to the shelf marker to establish how far the box landed from target. This was done at each of the box corners, and the largest dimension was used in the study. An exact outside dimension outline of the box was drawn on the shelf for the subjects to aim for placement. Figure 31 shows the box is parallel and to the right and below the target. At each corner, the deviation is measured for front to front and side to side deviation. An example of the front to back deviation is shown with the front left corner; an example of the side to side deviation is shown with the top right corner. Because the box could be placed on an angle (not exactly parallel to the target), the largest deviation of the four corners was used in the analysis for the side to side deviation and for the front to back deviation.

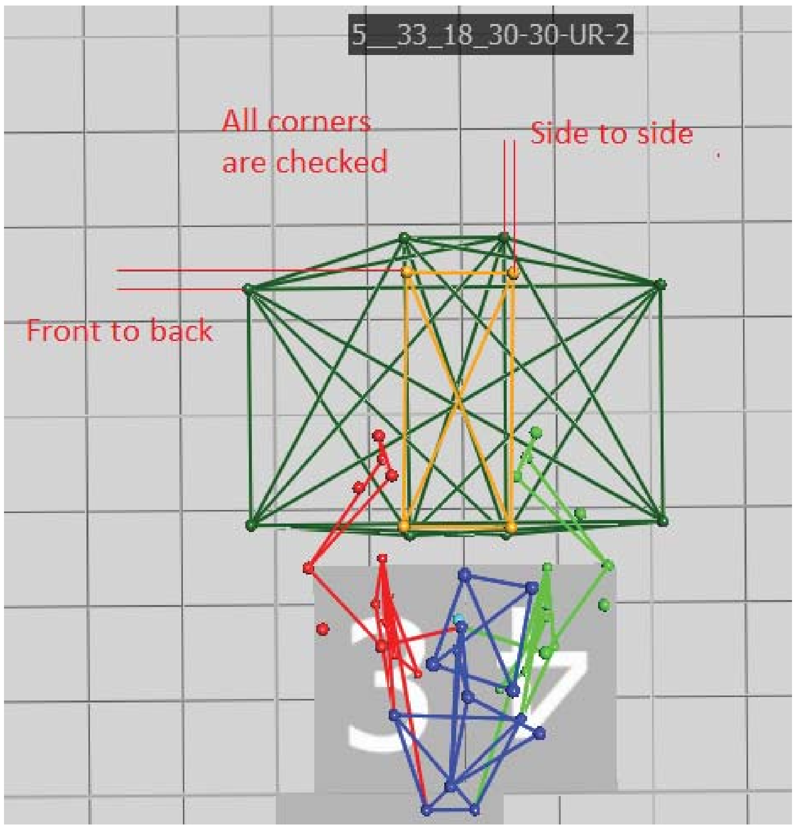

Figure 31. Relations of the markers on the box and table

Careful placement

Evaluation of how carefully the box is placed was accomplished by reviewing the trajectories of the markers placed on the box in relation to the shelf as the box made its way to the target. The box either landed carefully or not carefully. If the box was way off target it was counted as not being placed carefully. Further explanation of what was observed is given in the Results section.

Motion capture

The motion capture data were post-processed to fill any gaps and remove any noise, such as markers jumping. An inspection was preformed to ensure the subject's feet properly landed on the force plates and to ensure that the shelf height and shelf space used during the trail matched the configuration management identifier. The motion capture trial was then shortened from the full lift, from ground to the shelf, to just the motion of the box entering the shelf and landing. The first of each unique lift was considered a practice lift, and the second of each unique lift was used in this analysis.

Biomechanical forces to L5/S1

The pre-processed motion capture was then modeled in the Box Lifting Model to generate the kinetic data. The AB Technology spine joint forces are reaction forces in the spherical joint. AB Technology uses optimization to generate the muscle forces for the entire body. This model was used to generate the anterior/posterior (shear loading) and proximal/distal (compression loading) L5/S1 dynamic forces.

CHAPTER 5 RESULTS

The independent variables were: box weight, shelf height, and shelf space. The dependent variables were: accuracy, carefulness, time, and forces to the spine. The general linear model approach, where subjects were treated as random effects, was used for the analysis of accuracy of placing the box (front to back and side to side), as well as forces to the lower back (proximal/distal and anterior/posterior), and the amount of time to place the box. This approach accounts for the repeated measures within each subject. Two-sided 95 percentage confidence intervals were also used in the analysis of variance. The binary logistic model was used for the binary response variable to analyze the control of the box during placement of the box. The statistical analysis was performed in Minitab 17.

For all the responses, the normal probability plot, the versus fits, the histogram of residuals, and the versus order were used to check the model assumptions. The normal probability plot checks the normality assumption of the residuals. For all the responses, the data points line up along the straight line; thus, there was no reason to doubt the normality assumption. The versus fits, plots the residuals against the model predictions, and showed good results by not showing a funnel shape in any of the responses. The histogram of residuals is also used to check the normality assumption. The bell-shaped curve was found for all responses. The versus order checks to see if there is a trend in the order of the observations to assess independence. No increase or decrease in the path of the points occurred when moving from left to right, so the assumptions were satisfied for all responses. To get a better fit for the response variables for the accuracy of placing the box, and for time, the response variables were transformed into natural log.

There were two subject-specific variables: subject height and subject strength. The subject strength variables were collected at the 30" shelf and at the 50" shelf. For the two strength variables, the correlation is high, 0.853, where a perfect correlation would be 1. Thus, in the statistical analysis, only the subject strength from the 30" self and the subject height were applied.

For each of the research areas, placement accuracy, placement control, time, and spinal forces; tables based on the coefficient magnitudes, were provided to describe the relation of subject height and/or subject strength to each box configuration and to restricted and unrestricted shelf space. As categories for subject height, the min, max, and mean subject heights were used. These values are close to the FAA HFDS 5^{th}, 50^{th}, and 95^{th} percentile human height. Table 16. The same was done for the subject strength; however, for the categories for subject strength there were no related FAA HFDS strength values provided for humans with arms reaching out as when holding an avionics box. See Table 17.

To generate the values in these tables, an equation was used to convert the coefficients into the statistical values. An example equation, as was used for time, is: Log (time) = $-2.089-0.2236*(I_{W=30}) - 0.4224*(I_{W=45}) + 0.1252*(I_{=Restricted}) - 0.0786*(I_{H-50}) + 0.001964*Height$. In the previous equation, all the variables that look like (I_{W-45}) are set to 1 when the condition in the subscript is satisfied, and are set to 0 when the condition is not satisfied. By using the exponential function, the statistical values were transformed into centimeters for accuracy of placing the box, and to seconds for time.

The same equation was used for converting the proximal/distal, and anterior/posterior spinal force coefficients into the statistical values. The spinal forces had a good fit and remained in newtons. The exponential function was not needed for transformation.

The same equation was used for converting the control coefficients into the statistical values. The statistical results for control were then converted with logistic function using the form 1/(1+exp(-y)), where y is the values generated from the equation.

Table 16 Subject height - min, mean, max

FAA standard (mm)		
5th	50th	95th
1647	1755	1867
This study		
Min	Mean	Max
1622	1731	1860

Table 17 Subject strength - min, mean, max

This study (lbf)		
	Min	Max
50" shelf	12.0	44.0
30" shelf	7.6	45.0
Average	9.8	44.5

Accurate placement – front to back

When the experiment was designed, it was anticipated the boxes would be landing on target; however, that was not the case. There was a wide range of landings. Figure 32 shows two extremes, where the box landed on target and the box landed far off target.

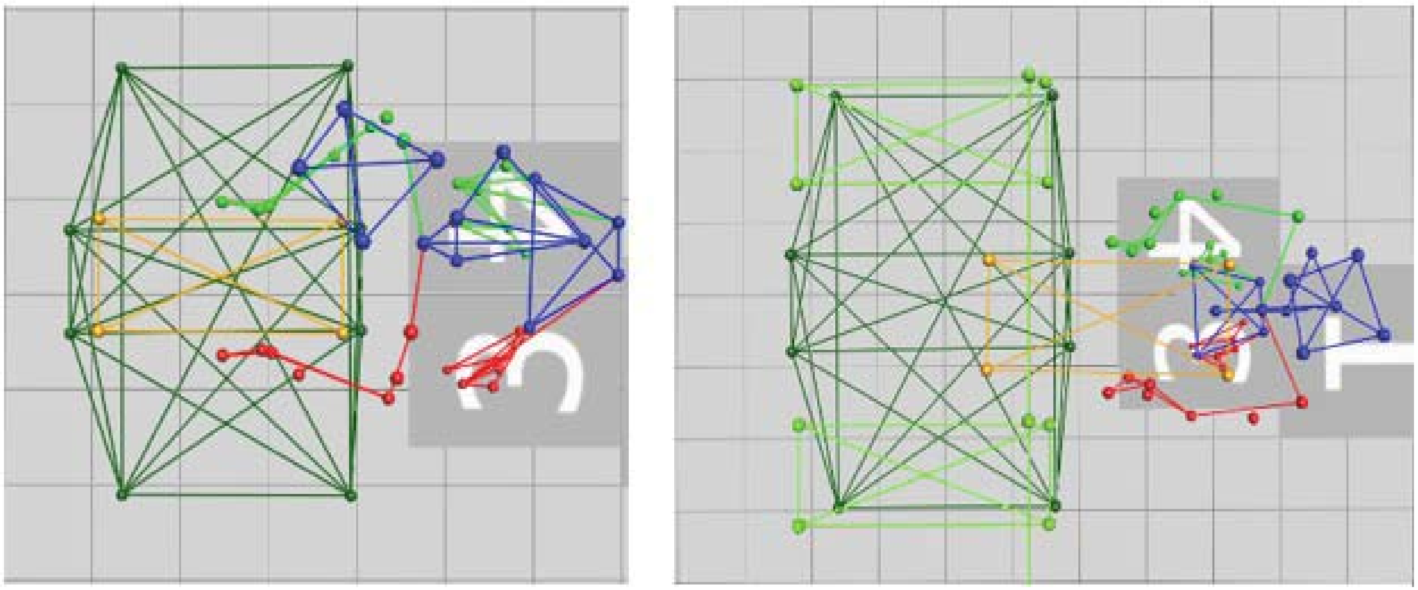

Figure 32. Box placed on and off target

The graph shows that, as the weight increases in restricted space, the front to back deviation from the target is increased. However, when looking at the shelf height, this is not consistent, as seen with the 15-pound box in restricted space, and the 30-pound box in unrestricted space. It improves at the 50" shelf height. See Figure 33.

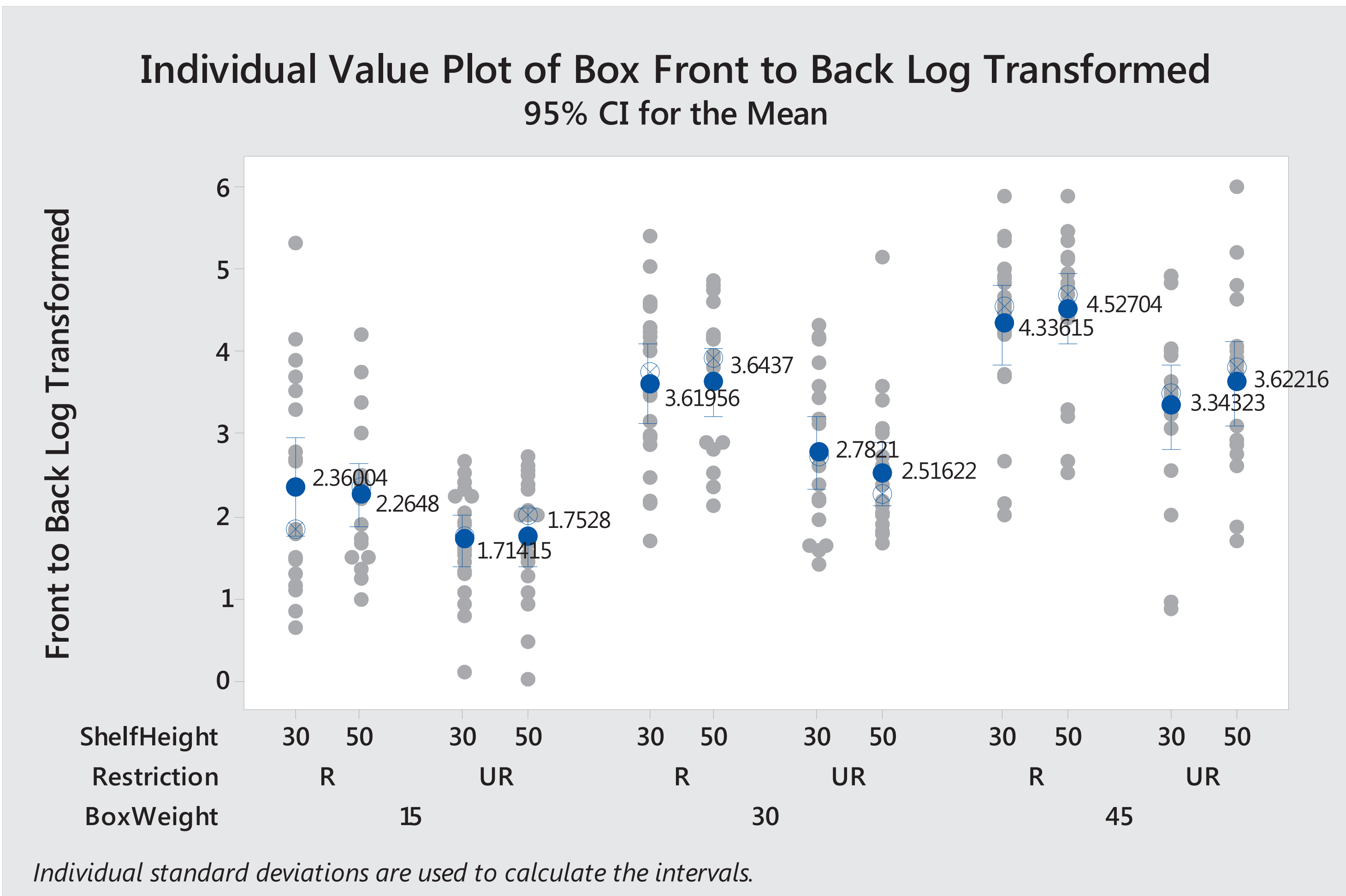

Figure 33. Box front to back log transformed

Within the 20 subjects, only one of the subjects, subject 1 with an average of 0.97 cm and SD of 0.45 cm, consistently placed the box near to the target in the front to back direction for all lifts. See Table 18.

Table 18. Front to back placement comparison (cm)

Subject	1	2	3	4	5	6	7	8	9	10
Mean	0.97	2.03	2.55	3.30	1.59	5.93	10.61	3.79	4.34	5.21
SD	0.45	2.20	3.44	4.45	1.79	8.17	8.53	3.43	4.22	4.36

Subject	11	12	13	14	15	16	17	18	19	20
Mean	1.32	4.21	3.75	7.13	6.83	1.98	3.66	2.89	3.73	15.60
SD	1.11	3.84	3.39	6.40	5.22	2.34	4.41	3.54	6.28	14.92

For back to front accuracy, there were many cases where the placement was outside of Sabry's recommendation of 5 cm on either side of the load (Ridd, 1985). The 45-50-R configuration had the highest count of 16 out of the 20 subjects. See Table 19.

Table 19 Count of boxes placed outside of Sabry's 5 cm

15-30-UR	15-30-R	15-50-UR	15-50-R	30-30-UR	30-30-R	30-50-UR	30-50-R	45-30-UR	45-30-R	45-50-U	45-50-R
0	2	0	1	3	10	1	11	5	15	7	16

Based on the analysis of variance approach, where the subject was treated as a random effect, shelf height (p-value=0.76) was not significant, and was removed from the model. Then, the model was run without the shelf height, the box weight with a (p-value=0.000) and restricted shelf-space with a (p-value=0.000) were both significantly associated with placement accuracy as measured from front to back.

Based on the analysis of variance coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, was placed more off target, which is significant with a (p-value=0.000).

To incorporate subject-specific covariates, namely height and strength, an alternative general linear model was considered. This model is less efficient than the previous approach, as the subject-specific variability is attributed to subject height and strength only, and the rest of the variability is absorbed by residual error, which ultimately could make the p-values larger. Using this alternative model, where subject characteristics were captured by subject strength and subject height, and where subjects were treated as random effects, shelf height with a (p-value= 0.955) was not significant and was removed from the model. Then the model was run without the shelf height, and box weight with a (p-value=0.000), shelf-space with a (p-value=0.000), subject height with a (p-value=0.000), and subject strength with a (p-value=0.010) were all significantly associated with placement accuracy as measured from front to back.

Since shelf height was not significant, the only interaction analysis attempted was between box weight and shelf space. The interactions between box weight and shelf space was not significant, so this interaction was left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, was placed more off target, which is significant with a (p-value=0.000).

With a negative coefficient, the taller subjects, as compared to the shorter subjects, on average, will have less deviation (error) from target, which is significant with a (p-value=0.000). The stronger subjects, as compared to the weaker subjects, on average, will have less deviation (error) from target, which is significant with a (p-value=0.010).

Based on the alternative model coefficient magnitudes, Table 20 describes the relation of subject height and strength to each box weight and to restricted and unrestricted shelf space. Shelf height was not significant and was not included. For each of the box weight configurations, the table shows the front to back deviations in the restricted shelf space, as compared to the unrestricted shelf space, which, on average, increases. As the subject height increases, the front to back deviations, on average, decrease. As the subject strength increases, the front to back deviations, on average, decrease.

Table 20 Front to back - subject height, strength and shelf space

Front to back (cm)												
Subject Height	Min~5 Percentile				Min~50 Percentile				Min~95 Percentile			
Subject Strength	Min		Max		Min		Max		Min		Max	
Shelf Space	UR	R	UR	R	UR	R	UR	R	UR	R	UR	R
15	1.0	2.3	0.5	1.2	0.7	1.6	0.4	0.8	0.4	1.0	0.2	0.5
30	3.0	7.0	1.6	3.7	2.0	4.7	1.1	2.5	1.3	3.0	0.7	1.5
45	6.6	15.5	3.5	8.1	4.5	10.4	2.3	5.4	2.8	6.5	1.5	3.4

Accurate placement – side to side

The graph does not show a consistent pattern, mainly with the 30-pound box. The 45-pound box does have higher deviation s in space as compared to the 15-pound box. See Figure 34.

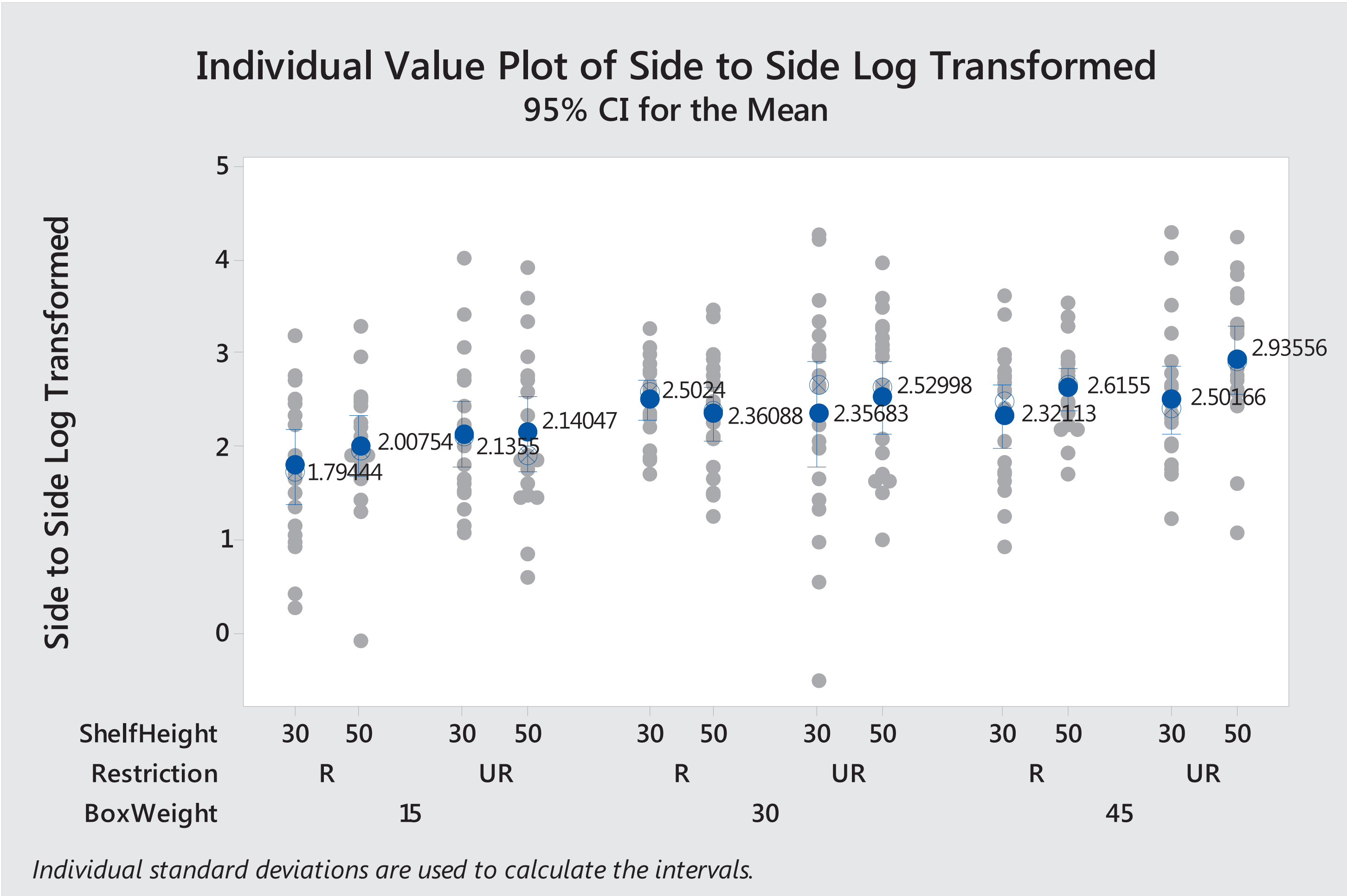

Figure 34. Box side to side log transformed

When comparing this side to side graph in Figure 34 with the front to back graph in Figure 33, it is more noticeable in the front to back graph that the distance from target is increasing more as the box weight increases, and that the distance from target is increasing more in the restricted shelf space.

For the side to side accuracy, most all of the placements fell within Sabry's recommendation of 5 cm on either side (Ridd, 1985). There was one subject that was outside this 5 cm for all of his placements in the unrestricted shelf. There was only one other subject that went outside of Sabry's recommendation, and this was at 45-30-UR configuration, which was only 1 of the 12 placements.

Based on the analysis of variance approach, where subjects were treated as random effects, the box weight with a (p-value=0.00), the shelf height with a (p-value=0.054), and restricted shelf-space with a (p-value=0.049) were all significantly associated with placement accuracy as measured from side to side.

Based on the analysis of variance coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, was placed more off target, which is marginally significant with a (p-value= 0.054). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, was more on target, which is marginally significant with a (p-value= 0.049).

Using an alternative model, where subject characteristics were captured by subject strength and subject height, and where subjects were treated as random effects, subject strength with a (p-value= 0.539) was not significant and was removed from the model. Then the model was run without the subject strength. Box weight with a (p-value=0.000), shelf height with a (p-value= 0.102), shelf-space with a (p-value= 0.095), and subject height with a (p-value= 0.020) were all significantly associated with placement accuracy as measured from side to side.

There were no interactions with box weight, shelf height, and shelf space, so these interactions were left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, was placed more off target, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, was placed more off target, which is marginally significant with a (p-value= 0.054). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, was placed more on target, which is marginally significant with a (p-value= 0.049).

With a negative coefficient, the taller subjects, on average, will have less deviation (error) from target than shorter subjects, which is significant with a (p-value=0.020).

Based on the alternative model coefficient magnitudes, Table 21 describes the relation of subject height to each box weight/shelf height configuration and to restricted and unrestricted shelf space. For each box weight/shelf height configurations, the table shows the distance off target in the restricted shelf space, as compared to the unrestricted shelf space, which, on average, is less. As the subject height increases, the distance off target on average decreases for all cases.

Table 21 Side to side - subject height and shelf space

Side to side (cm)						
Subject Height	Min (~5th percentile)		Mean (~50th percentile)		Max (~95th percentile)	
Shelf Space	UR	R	UR	R	UR	R
15-30	0.91	0.77	0.75	0.64	0.60	0.51
15-50	1.07	0.90	0.89	0.75	0.71	0.60
30-30	1.38	1.17	1.14	0.97	0.91	0.77
30-50	1.62	1.37	1.34	1.14	1.08	0.91
45-30	1.61	1.36	1.34	1.13	1.07	0.90
45-50	1.90	1.61	1.57	1.33	1.26	1.06

The restricted case was a little more on target than the unrestricted cases. This may be because the box was not installed all the way on target in the front to back direction in the restricted shelf, or because the placement of the box within the restricted space is performed by inserting the box between the two shelves and two boxes as it is being placed, as compared to the unrestricted shelf space, where there is open space with no restrictions to top or sides, and the box is not inserted as it is placed on the shelf.

Careful placement

The trajectories of the box were observed as the box is making its way to the target on the shelf. As the box landed on or off target, the observed landings included:

1. All four corners land close at the same time with no skipping or scraping
2. Left front corner hits first, then other corners hit before landing
3. Right front corner hits first, then other corners hit before landing
4. Left back corner hits first, then other corners hit before landing
5. Right back corner hits first, then other corners hit before landing
6. Left front corner hits, and there is skipping or scraping
7. Right front corner hits, and there is skipping or scraping
8. Left back corner hits, and there is skipping or scraping
9. Right back corner hits, and there is skipping or scraping
10. Both of the back two corners land first, then front two corners land, no skipping or scraping
11. Both of the front two corners land first, then the back two corners land, no skipping or scraping

12. Both of the back two corners land first, then front two corners land, includes skipping or scraping
13. Both of the front two corners land first, then the back two corners land, includes skipping or scraping
14. Left side lands first, then the right-side lands
15. Right side lands first, then the right-side lands
16. Underside of box hits the shelf, then the front two corners land.

Figure 35 shows three examples of a landing that were not controlled: (1) front corners land and then the corners scrape as the box makes its way to the target; (2) the bottom of the box hits the shelf edge, then the box is pushed up to the target; and (3), the front corners hit and skip along as the box makes its way to the target. If the box was way off target, it was considered out of control, and was classified as not being carefully placed.

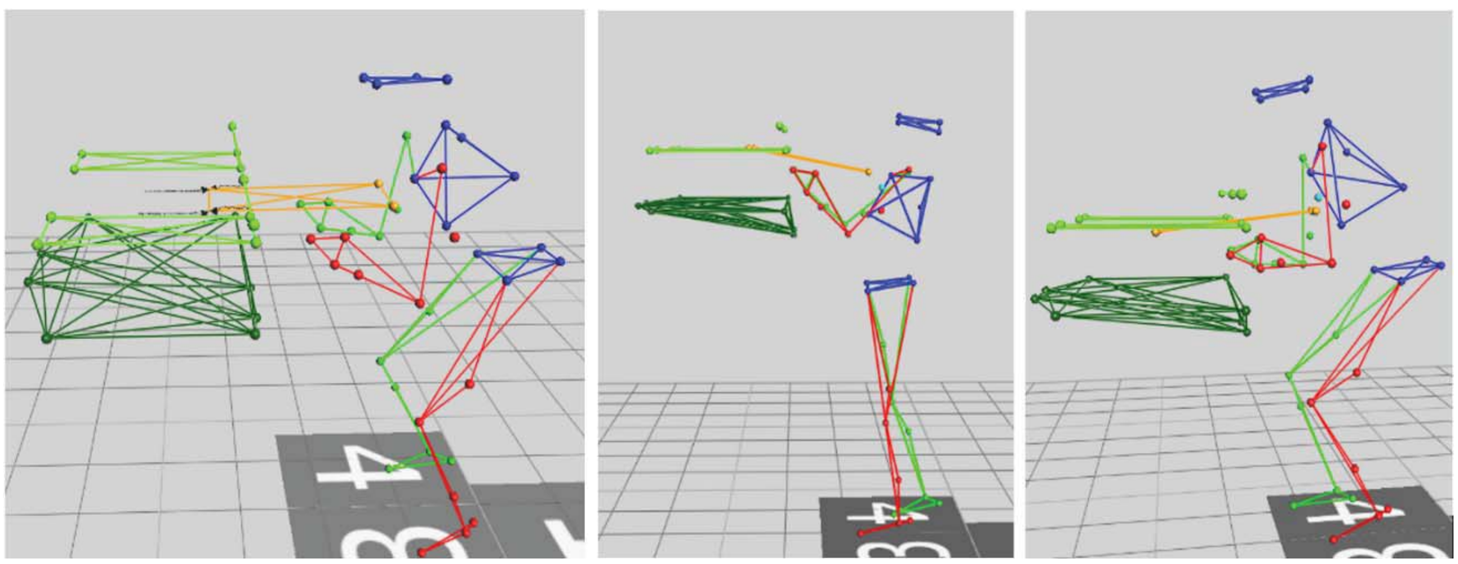

Figure 35. Examples of box not in control

Based on the binary logistic model approach, shelf height with a (p-value=1.000) was not significant and was removed from the model. Then the model was run without the shelf height, and the box weight with a (p-value=0.000) and restricted space with a (p-value=0.000) were both significantly associated with the controlled placement of the box.

Based on the model coefficient signs, with the 30-pound box, as compared to the 15-pound box, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000). With the 45-pound box, as compared to the 15-pound box, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000). With the box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000).

Using an alternative model where subject-specific characteristic were incorporated, shelf height with a (p-value= 0.539) was not significant and was removed from the model. Then the model was run without the shelf height, and the box weight with a (p-value=0.000), self-space with a (p-value= 0.000), subject height with a (p-value= 0.002), and subject strength with a (p-value=0.000) were all significantly associated with careful placement.

Since the shelf height was not significant, the only interaction analysis were with box weight and shelf space. The interactions between box weight and shelf space were not significant, so this interaction was left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000). With the 45-pound box, as compared to the 15-pound box, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000). With the box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, there is a smaller probability of controlling the box, which is significant with a (p-value=0.000).

With positive coefficient the taller subjects, on average, will have more control of the box compared to shorter subjects, which is significant with a (p-value= 0.002); and the stronger subjects, on average, will have more control of the box compared to the weaker subjects, which is significant with a (p-value= 0.000).

Based on the alternative model coefficient magnitudes, Table 22 describes the relation of subject height and strength to each box weight and to restricted and unrestricted shelf space. Shelf height was not significant and was not included. For each of the box weight, the table shows that, in the restricted shelf space, as compared to the unrestricted shelf space, on average, there is a smaller probability of controlling the box. As the subject height increases, there is a greater probability of controlling the box. As the subject strength increases, there is a greater probability of controlling the box.

Table 22 Control - subject height, strength and shelf space

Control (probability)												
Subject Height	Min (~5th percentile)				Mean (~50th percentile)				Max (~95th percentile)			
Subject Strength	Min		Max		Min		Max		Min		Max	
Shelf Space	UR	R	UR	R	UR	R	UR	R	UR	R	UR	R
15	0.29	0.07	0.89	0.62	0.54	0.18	0.96	0.82	0.80	0.44	0.99	0.94
30	0.02	0.00	0.34	0.09	0.07	0.01	0.59	0.22	0.20	0.05	0.83	0.49
45	0.01	0.00	0.13	0.03	0.02	0.00	0.29	0.07	0.06	0.01	0.58	0.21

Time to place the box

The graph shows that, as the box weight increases, the time to place the box is less. The 50" shelf takes less time than the 30" shelf for all cases except for the 30-pound box in the unrestricted space. For all cases, except for the 45-pound box in the 50" shelf, restricted space takes more time to place the box. See Figure 36.

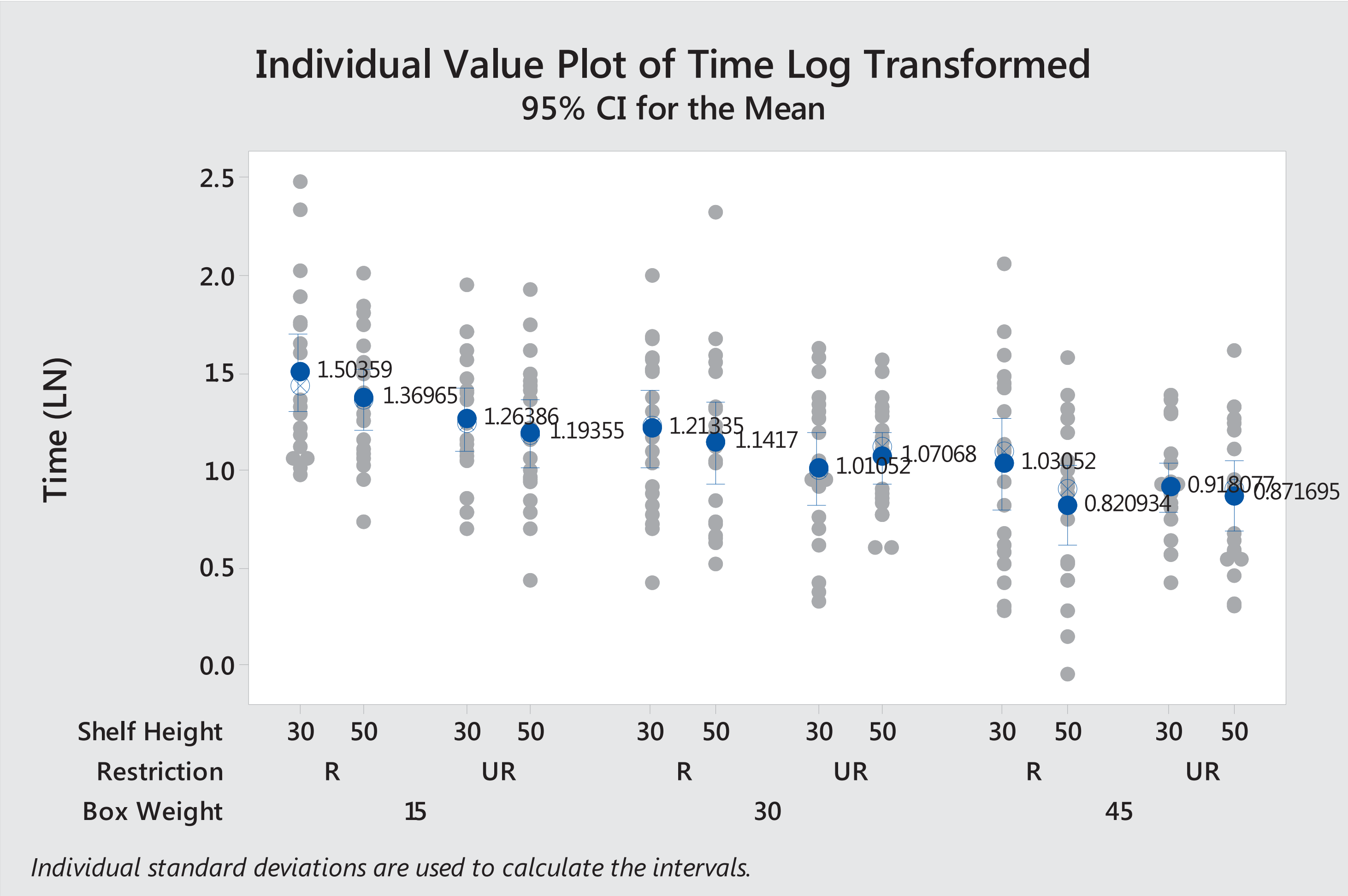

Figure 36. Time to place box log transformed

Based on the analysis of variance approach, where subjects were treated as random effects, the box weight with a (p-value=0.000), the shelf height with a (p-value=0.007) and restricted shelf space with a (p-value=0.000) were all significantly associated with the time to place the box on target.

Based on the analysis of variance coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, resulted in a decrease in time to place the box, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in a decrease in time to place the box, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease in the time to place the box, which is significant with a (p-value= 0.007). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in an increase in time to place the box, which is significant with a (p-value= 0.000).

Using an alternative model, where a subject-specific characteristics were incorporated, including subject height and strength for each subject, subject strength was not significant with a (p-value=0.167) and was removed from the model, and the model was run again. The box weight remained with a (p-value=0.000), shelf height changed to (p-value= 0.097), the shelf space also changed to (p-value= 0.008), and the subject height with a (p-value=0.000). This model is less efficient, as the subject-specific variability is only attributed to subject height, and thus the rest of the variability is absorbed by residual error which would make the shelf height and shelf space p-values larger.

The interactions between box weight, shelf height, and shelf space were not significant, so this interaction was left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, resulted in a decrease in time to place the box, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in a decrease in time to place the box, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease in the time to place the box with the alternative model, which is marginally significant with a (p-value= 0.097). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in an increase in time to place the box, which is significant with a (p-value= 0.008).

With a positive coefficient, the taller subjects, on average, will take more time than shorter subjects, which is significant with a (p-value= 0.000).

Based on the alternative model coefficient magnitudes, Table 23 describes the relation of subject height to each box weight/shelf height configuration, and to restricted and unrestricted shelf space. For each box weight/shelf height configurations, the table shows that, in the restricted shelf space, as compared to the unrestricted shelf space, on average, it takes more time to make the placement. As the subject height increases, the placement time, on average, increases.

Table 23 Time - subject height and shelf space

Time (sec)						
Subject Height	Min (~5th percentile)		Mean (~50th percentile)		Max (~95th percentile)	
Shelf Space	UR	R	UR	R	UR	R
15-30	2.99	3.39	3.71	4.20	4.78	5.42
15-50	2.77	3.14	3.43	3.88	4.42	5.01
30-30	2.39	2.71	2.96	3.36	3.82	4.33
30-50	2.21	2.51	2.74	3.10	3.53	4.00
45-30	1.96	2.22	2.43	2.75	3.13	3.55
45-50	1.81	2.06	2.25	2.54	2.90	3.28

It can be seen in Table 24 for the 20 subjects that the average front to back distance of the box landing on the target is closer to the target in the unrestricted shelf space, and further away in the restricted shelf space. Thus, the time comparison is not as accurate as if all the boxes landed close to the same location on the target. If the boxes had landed closer to target in the restricted space, the time to place the box would have been greater.

Table 24. Front to back distance off target (cm)

15-30-UR	15-30-R	15-50-UR	15-50-R	30-30-UR	30-30-R	30-50-UR	30-50-R	45-30-UR	45-30-R	45-50-U	45-50-R
0.67	2.54	0.72	1.42	2.40	5.85	2.07	5.28	4.44	11.05	6.63	12.59

Biomechanical stresses – proximal/distal

The graph shows that, as weight increases, the forces to the spine increase. On the 30" shelf, the forces to the spine increase. With all cases except with the 15-pound box in the 30" shelf, the forces to the spine increase when the box is installed in the unrestricted space. See Figure 37.

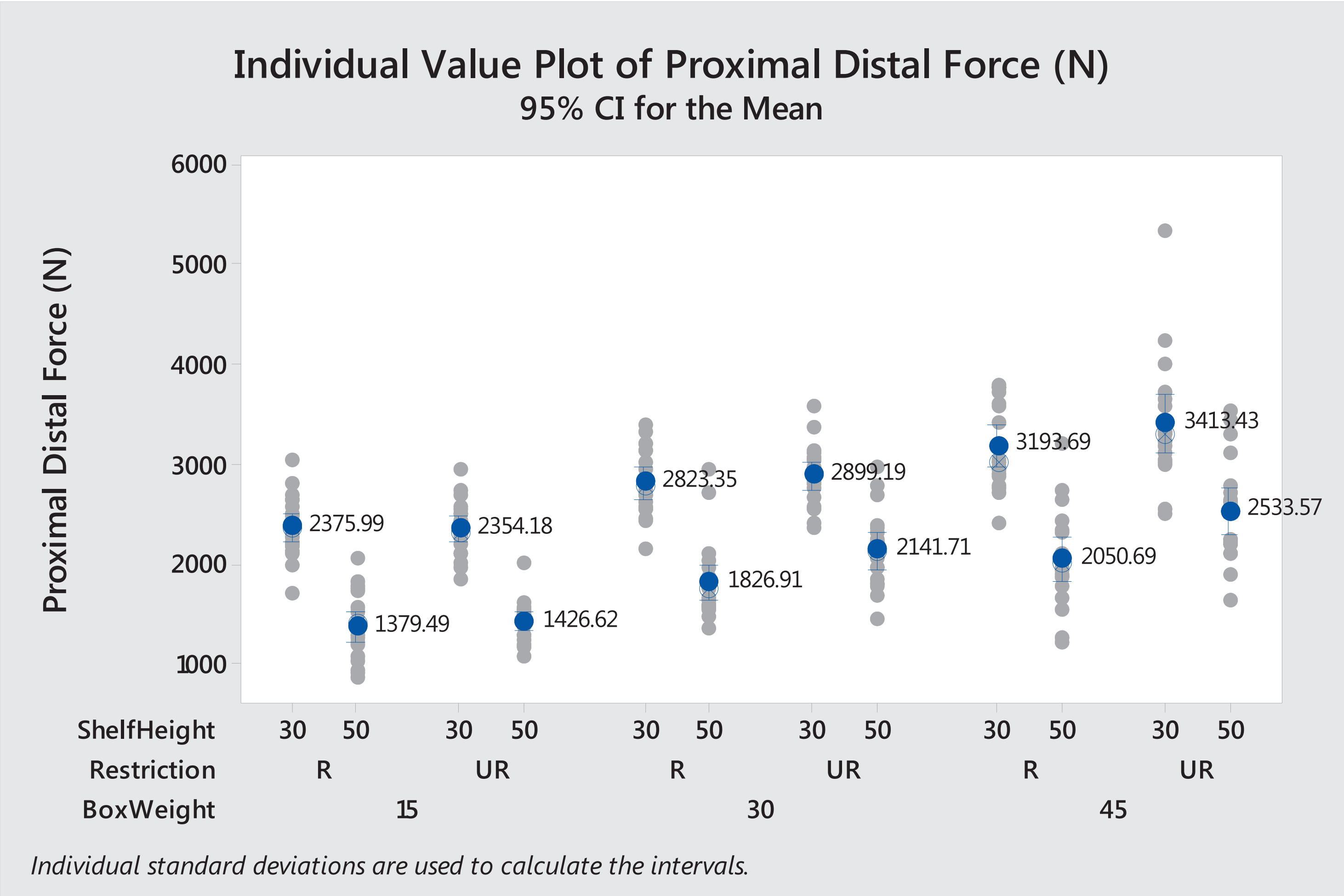

Figure 37. Proximal distal (N)

Based on the analysis of variance approach, with subjects treated as random effects, the box weight with a (p-value=0.000), shelf height with a (p-value=0.000), and restricted shelf-space with a (p-value=0.000) were all significantly associated with the biomechanical stresses in the proximal/distal direction.

Based on the analysis of variance coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, resulted in an increase of proximal/distal forces, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in an increase of proximal/distal forces, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease of proximal/distal forces, which is significant with a (p-value= 0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in a decrease of proximal/distal forces, which is significant with a (p-value= 0.000).

Using an alternative model, where subject-specific characteristics were incorporated, incorporating subject height and strength for each subject, subject strength was not significant with a (p-value= 0.496), and was removed from the model. The model was run again, and box weight, shelf height, and restricted shelf-space remained significant with a (p-value= 0.000). Subject height is significantly associated with the L5/S1 spine forces with a (p-value= 0.000).

The interactions between box weight, shelf height, and shelf space were not significant, so this interaction was left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, resulted in an increase of proximal/distal forces, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in an increase of proximal/distal forces, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease of proximal/distal forces, which is significant with a (p-value= 0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in a decrease of proximal/distal forces, which is significant with a (p-value= 0.000).

With a positive coefficient, the taller subjects, on average, will have more stress to the spine than shorter subjects, which is significant with a (p-value=0.000).

Based on the alternative model coefficient magnitudes, Table 25 describes the relation of subject height to each box weight/shelf height configuration and to restricted and unrestricted shelf space. For each box weight/shelf height configuration, the table shows the proximal/distal spinal forces in the restricted shelf space. as compared to the unrestricted shelf space, on average, decreases. As the subject height increases, the proximal/distal spinal forces, on average, decreased.

Table 25 Proximal distal - subject height and shelf space

Proximal distal (N)						
Subject Height	Min (~5th percentile)		Mean (~50th percentile)		Max (~95th percentile)	
Shelf Space	UR	R	UR	R	UR	R
15-30	2210.17	2023.77	2452.89	2266.49	2742.10	2555.70
15-50	1260.07	1073.67	1502.79	1316.39	1792.00	1605.60
30-30	2748.87	2562.47	2991.59	2805.19	3280.80	3094.40
30-50	1798.77	1612.37	2041.49	1855.09	2330.70	2144.30
45-30	3123.97	2937.57	3366.69	3180.29	3655.90	3469.50
45-50	2173.87	1987.47	2416.59	2230.19	2705.80	2519.40

Because the box was placed closer to the subject in the restricted shelf space, there is less of a moment arm between the L5/S1 joint axis and the box, which would result in less stress to the spine than when the boxes are placed further away from the subject and closer to the target. Thus, the biomechanical L5/S1 forces comparison would be more accurate if all the boxes landed close to the same location on the target.

Biomechanical stresses – anterior/posterior

The following graph shows that, as weight increases, the forces to the spine are higher for all cases. In the 30" shelf, the forces to the spine are higher than in the 50" shelf for all cases. In the unrestricted shelf space, the forces to the spine are higher when the box is installed in the unrestricted space, except for one of the cases with the 15-pound box placed in the 30" unrestricted shelf, in which the forces to the spine are lower. See Figure 38.

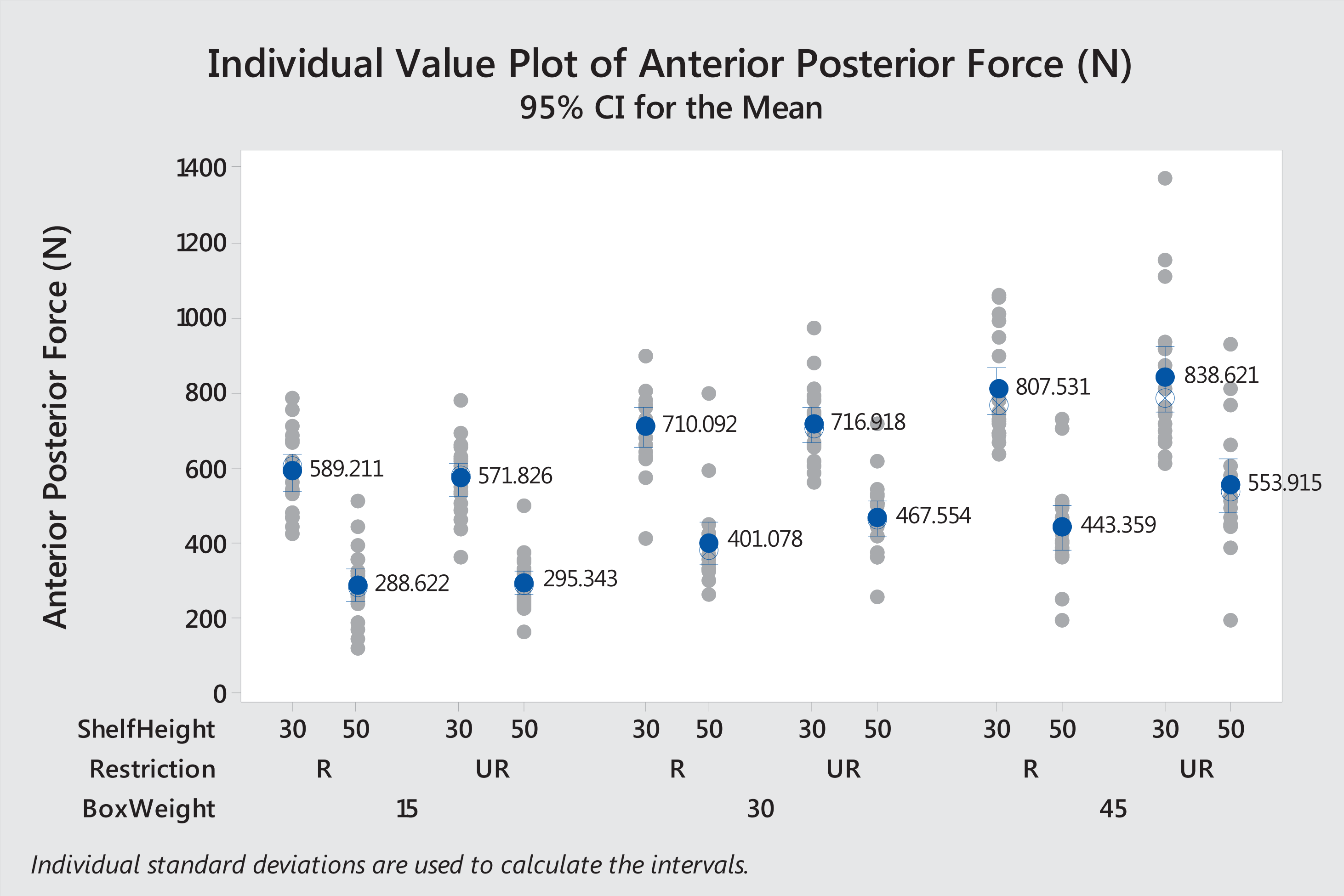

Figure 38. Anterior posterior (N)

Based on the analysis of variance approach, where subjects were treated as random effects, the box weight with a (p-value=0.000), the shelf height with a (p-value=0.000), and restricted shelf space with a (p-value=0.000) were all significantly associated with the biomechanical stresses in the anterior/posterior direction.

Based on the analysis of variance coefficient signs, the 30-pound box, as compared to the 15-pound box, resulted in an increase of anterior/posterior forces, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in an increase of anterior/posterior forces, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease of anterior/posterior forces, which is significant with a (p-value= 0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in a decrease of anterior/posterior forces, which is significant with a (p-value= 0.002).

Using an alternative model, where subject-specific characteristics were incorporated, incorporating subject height and strength for each subject, the p-value for shelf space increased to (p-value= 0.033). The box weight and shelf height remained significant with a (p-value= 0.000). Subject strength with a (p-value= 0.006) and subject height with a (p-value= 0.062), are significantly associated with the L5/S1 spine forces.

The interactions between box weight, shelf height, and shelf space was not significant, so this interaction was left out of the model.

Based on the alternative model coefficient signs, the 30-pound box, as compared to the 15-pound box, on average, resulted in an increase of anterior/posterior forces, which is significant with a (p-value=0.000). The 45-pound box, as compared to the 15-pound box, on average, resulted in an increase of anterior/posterior forces, which is significant with a (p-value=0.000). The box placed in the 50" shelf height, as compared to the 30" shelf height, on average, resulted in a decrease of anterior/posterior forces, which is significant with a (p-value= 0.000). The box placed in the restricted shelf space, as compared to the unrestricted shelf space, on average, resulted in a decrease of anterior/posterior forces, which is significant with a (p-value= 0.033).

With a positive coefficient, the taller subjects, on average, will have more stress to the spine, which is significant with a (p-value= 0.062). With a negative coefficient, the stronger subjects, on average, will have less stress to the spine, which is significant with a (p-value= 0.006).

Based on the alternative model coefficient magnitudes, Table 26 describes the relation of subject height and strength to each box weight/shelf height configuration and to restricted and unrestricted shelf space. For each box weight/shelf height configurations, the table shows the anterior/posterior spinal forces in the restricted shelf space, as compared to the unrestricted shelf space, which is, on average, less. As the subject height increases, the anterior/posterior spinal forces, on average, increase. As the subject strength increases, the anterior/posterior spinal forces, on average, decrease.

Table 26 Anterior posterior - subject height, strength and shelf space

Anterior posterior (N)												
Subject Height	Min~5 Percentile				Min~50 Percentile				Min~95 Percentile			
Subject Strength	Min		Max		Min		Max		Min		Max	
Shelf Space	UR	R	UR	R	UR	R	UR	R	UR	R	UR	R
15-30	616	581	526	491	640	606	550	516	670	635	580	546
15-50	314	280	224	190	338	304	248	214	368	334	278	244
30-30	754	720	664	630	779	745	689	655	808	774	718	684
30-50	452	418	362	328	477	443	387	353	506	472	417	382
45-30	842	808	752	718	866	832	777	742	896	862	806	772
45-50	540	506	450	416	565	530	475	441	594	560	504	470

As explained previously, with proximal distal forces, the biomechanical L5/S1 forces comparison would be more accurate if all the boxes landed close to the same location on the target.

CHAPTER 6 DISCUSSION AND RECOMMENDATIONS

Front to back placement accuracy

Since the box weight and restricted shelf space are significant factors, the human factors or ergonomic designer will need to consider these when designing for front to back placement accuracy. Since the shelf height was not a significant factor, the ergonomic designer may not need to consider shelf height when designing for accurate front to back placement of a box in a restricted shelf. The ergonomic designer may want to consider using the human performance metrics values, as shown in Table 20, for the box weight factor when designing for front to back placement of a box accurately within restricted and unrestricted spaces. Table 27 is based on the interaction plot for box weight and shelf space. The ergonomic designer must keep in mind that these are average values, and there will be variances in performance, as shown previously.

Table 27. Box weight and shelf space - front to back

	Restricted	Unrestricted
15 lb.	1.09 cm	0.57 cm
30 lb.	3.78 cm	1.49 cm
45 lb.	8.49 cm	3.23 cm

Additionally, because subject strength and subject height are significantly associated with front to back placement, human factors engineering for operations may want to consider these when assigning personnel to the task of front to back placement accuracy.

Side to side placement accuracy

The box weight, shelf height, and shelf space are significant factors, and the human factors engineer or ergonomic designer may want to consider the human performance metrics in Table 28, 29, and 30 when designing for side to side placement of a box accurately within restricted and unrestricted spaces. These tables are based on the interaction plot. The ergonomic designer must keep in mind that these are average values, and there will be variances in performance as shown previously in the box plots.

The restricted case did better than the unrestricted case, as shown in Table 28 and 30. This is probably because, with the restricted shelf space, the box trajectory was insertion and placement as compared to the unrestricted shelf space, which had no restrictions to the top or sides of the box, or because the box was not installed all the way front to back in the restricted shelf.

Table 28. Box weight and shelf space – side to side

	Restricted	Unrestricted
15 lb.	0.67 cm	0.85 cm
30 lb.	1.14 cm	1.15 cm
45 lb.	1.18 cm	1.52 cm

Table 29. Box weight and shelf height – side to side

	30" Shelf	50" Shelf
15 lb.	0.71 cm	0.80 cm
30 lb.	1.14 cm	1.15 cm
45 lb.	1.12 cm	1.60 cm

Table 30. Shelf height and shelf space – side to side

	Restricted	Unrestricted
30"	0.91 cm	1.03 cm
50"	1.02 cm	1.26 cm

Additionally, because subject height is significantly associated with side to side placement, human factors engineering for operations may want to consider this when assigning personnel to the task of side to side placement accuracy.

Placement control of the box

The box weight and shelf space were both significant factors; however, the shelf height was not a significant factor. The probability of controlled placement of avionics boxes is not high, except for the 15-pound box in unrestricted space. See Table 31. Table 31 is based on the interaction plot for box weight and shelf space. The human factors engineer or ergonomic designer may want to avoid designing for boxes weighing 30 and 45 pounds where control is needed, and avoid boxes to be placed in restricted spaces where control is needed.

Table 31. Probabilities for not controlled

	Restricted	**Unrestricted**
15 lb.	0.55	0.23
30 lb.	0.95	0.73
45 lb.	0.95	0.90

Additionally, because subject height and subject strength are significantly associated with side to side placement, human factors engineering for operations may want to consider this when assigning personnel to the task of Placement Control.

Time to place box

The box weight, shelf height, shelf space, and subject height are significant factors. As the box weight increases, the time to place the box decreases. This is advantageous, since the installer is lifting the heavier boxes in less time. For most of the cases, it takes longer to place the box in the 30" shelf, and it takes longer to place the box in the restricted space. So the human factors engineer or ergonomics designer may want to consider avoiding box placements in the lower shelves and in the restricted shelf space.

Biomechanical stresses

For both the proximal/distal and anterior/posterior force to the spine, as the box weight is increased, the stresses to the spine increased as well; therefore, the human factors engineer or ergonomic designer would want to avoid the heavier 30-pound and 45-pound boxes. The stresses are less when placing the box on the 50" shelf as compared to the 30" shelf. Therefore, the human factors engineer or ergonomic designer would want to avoid placing the boxes on the lower 30" shelf. The lower stresses found in restricted shelf space would most likely have been higher if the boxes in this research would have been placed all the way on target; therefore, the human factors engineer or ergonomic designer would also want to avoid placing the boxes in a restricted shelf.

CHAPTER 7 CONCLUSION

The aim of this research was to determine: (1) how accurately the avionics box can be placed on target, (2) how carefully the avionics box can be placed on target, (3) how much time it takes to place the box on target, and (4) what are the biomechanical stresses to the lower back. This study also developed two biomechanical models: the S-Model and the Box Lifting Model. In addition, this study established a definition for Placement Control as careful and accurate placement.

The results determined that the Placement Control of the 15-pound box in unrestricted shelf space has the best average accuracy of front to back space of 0.57 cm, and the best probability for controlling the box was 0.77. It was shown that placing boxes accurately and carefully in restricted shelf space was not likely, given these boxes needed to be placed close to the target as within the space shuttle. For the 15-pound box in restricted space, the best average front to back accuracy was 1.09 cm, and the probability of controlling the box was 0.45. As the box weight increased, the accuracy and probability both decreased rapidly. For the 30-pound box, the average accuracy was 3.78 cm, and the probability of controlling the box was 0.05. For the 45-pound box, the average accuracy was 8.49 cm, and the probability of controlling the box was 0.05.

The L5/S1 forces were higher when the box weight increased and when the shelf height was lower. Since the box was not always placed all the way into the shelf front to back, especially as the box weight increased, the comparisons of L5/S1 forces to place the box is not as accurate as it would be if all the boxes were placed closer to the same location on target. If the box would have landed on target, the L5/S1 forces would most likely be higher when placing the box in the restricted shelf space. For safety reasons, the subjects were not forced to, but were only encouraged to place the box accurately and carefully on target.

As the box weight increases, the time to place the box is less. For most of the cases, it takes longer to place the box in the 30" shelf, and it takes longer to place the box in the restricted space, which is not good from a biomechanical aspect to stresses to the body. Since the box was not always placed all the way into the shelf front to back, especially as the box weight increased, the comparisons of time to place the box were not as accurate as they would be if all the boxes were placed closer to the same location on target.

Because there are no other studies available considering accurate and careful placement of boxes in restricted space, the human factors engineer or ergonomic designer may want to consider using the results of this paper, as outlined in the recommendations, when designing to a similar type lift configuration as the one studied in this paper. The human factors engineer or ergonomics designer need to consider that the technician on the production floor may over exert themselves to place the box accurately and carefully, and this could escalate the likelihood of increasing biomechanical stresses.

It is hoped that future studies will expand upon this study to develop and establish human limitation requirements for use in the FAA HFDS for accurate and careful placement of boxes in restricted and unrestricted spaces.

Limitations

- Because it was not safe to force the subjects to place the box exactly on target, the boxes did not all land near to the target. The 15-pound boxes landed closer to the target and further away from the subject, and the 45-pound boxes landed off target and closer to the subject. Ideally, for time and biomechanical comparison, it would be better for the 15, 30, and 45-pound boxes to all land close to the target.

Future research

- Continue studies for controlled and accurate placement where all the boxes land on target to evaluate the L5/S1 forces for restricted spaces.
- Further development and validation of the University of Miami Box Lifting Model by comparing the EMG muscle activity to the AB muscle activity of all 240 box placements.
- Further development and validation of the S-Model, possibly as a Vicon product that could interface with a muscle program.
- Further studies on Placement Control using, and expanding upon, the definitions of controlled and accurate placement.
- Further studies on Placement Control using, considering stresses to the body other than the lower back, such as the shoulders or wrist.
- Consider trained technician's performance to non-trained technician's performance for accuracy and control.
- Consider if practice lifts before the placement lift improves accuracy and control.
- Consider what materials could be used to strengthen the cold plate enough to withstand damages from placing the avionics box.
- Survey data (not required for this study) were collected on perceived body stresses in this Placement Control research that can be analyzed in future.

- Consider multiple transportation mode comparisons to validate findings and contribute to the best practices for Placement Control within the transportation industry (air, space, land, sea).
- Consider cost avoidance factor with fewer parts damaged as a result of best Placement Control practices.
- Consider impact of robotics, or other mechanical means, as an alternative to human capability for Placement Control.

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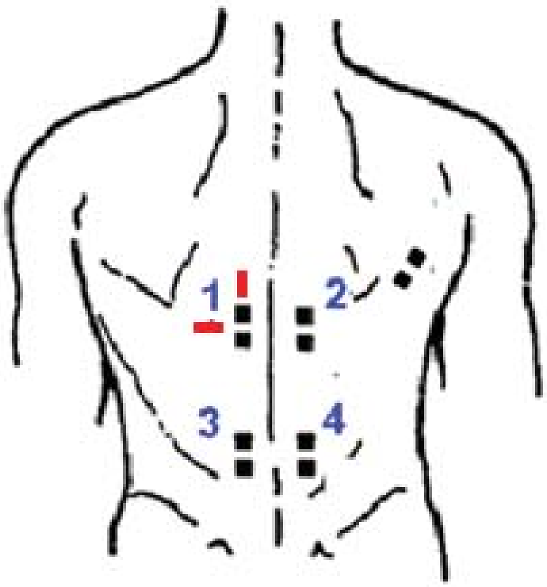
APPENDIX

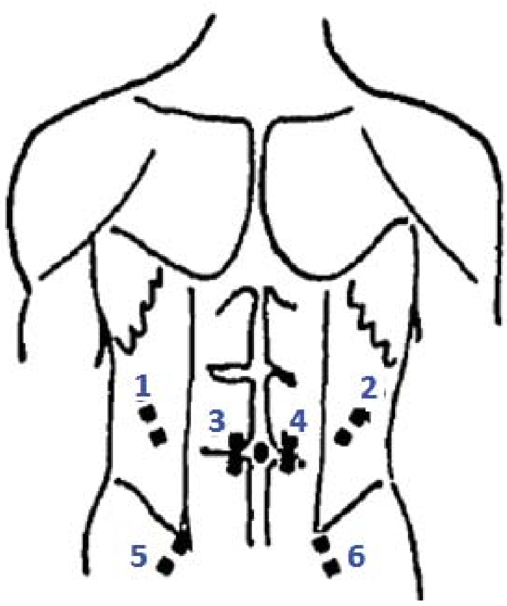
Lab procedure

Record anthropometric measurements.

Body Mass (kg)	
Height(mm)	
Leg Length	
Knee Width	
Ankle Width	
Shoulder Offset	
Elbow Width	
Wrist Width	
Hand Thickness	

Measure and mark the body for the reflective marker locations for T10 and LASI, RASI, LPSI and RPSI, and then for all EMG electrode locations. Example see the two short lines for EMG #1. Then for the EMG electrode locations, shave, sand, and clean areas. Then re-mark if needed.





EMG BOX A:

<u>Box A</u>: 1\2 Thoracic erector spinae, 5 cm lateral to T9 spinous process,

A: 3\4 Lumbar erector spinae, 3 cm lateral to L3 spinous process.

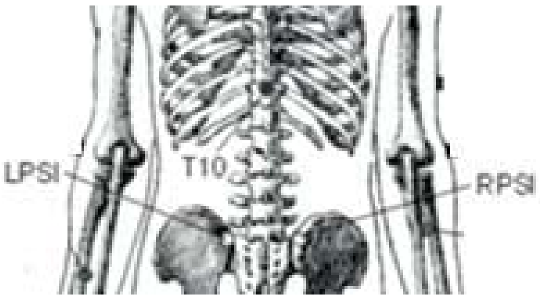
<u>Box B</u>: 1\2 External oblique, approximately 15 cm lateral to the umbilicus.

B: 3\4 Rectus abdominis, 3 cm lateral to the umbilicus; 2 cm above umbilicus.

B: 5\6 internal oblique, below the external oblique electrodes and just superior to the inguinal ligament.

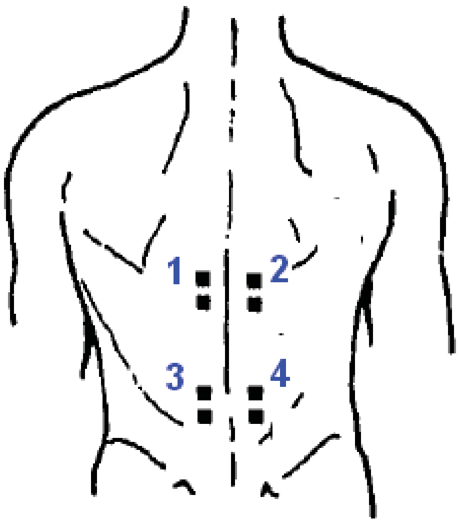
May not use. Latissimus dorsi, lateral to T9 over the muscle belly.

Locations for T10 LPSI and RPSI.



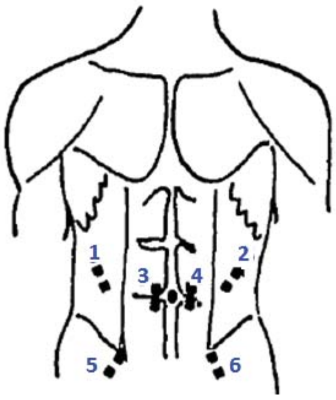
Locations for RASI and LASI

Then, to perform 2 MVC contractions for each muscle group. Place EMG electrodes on posterior (back), and in Vicon NEXUS list these as 1\2 and 3\4. And then do the exercise in picture, and collect MVC in NEXUS.



Then place the EMG electrodes for the anterior of body. And perform the 2 MVC for each muscle group. In NEXUS list these MVCs as 7\8, 5\10, 6\9

- Right EO/IO - 1/6 - Subject brings his right shoulder towards left knee. Lab assistant applies force to right shoulder.
- RA - 3/4 – Subjects brings both shoulders towards knees. Lab assistant applies force to both shoulders.
- Left EO/IO - 2/5 - Subject brings his left shoulder towards the right knee. Lab assistant applies force to left shoulder.



Place on the reflective markers and perform a static capture. Then perform two practice lifts and verify that all data are being collected. Begin the random lifts, and verify the data are being collected correctly after every lift. After performing the random box lifts the lifts are performed for the validation of the model.

Check complete	Random Box Lifts	Notes
	45-50-R-2	
	45-30-R	
	30-30-R-2	
	30-50-UR	
	15-50-UR	
	15-30-R-2	
	30-30-UR	
	30-50-R-2	
	15-50-R	
	30-30-UR-2	
	15-30-UR	
	45-30-UR	
	45-30-UR-2	
	15-50-UR-2	
	30-30-R	
	15-30-UR-2	
	30-50-UR-2	
	45-50-UR	
	45-30-R-2	
	15-30-R	
	15-50-R-2	
	30-50-R	
	45-50-R	
	45-50-UR-2	

	Model Validation	Notes
	15-30	
	15-30_2	
	30-30	
	30-30_2	
	15-50	
	15_50_2	
	30-50	
	30-50_2