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Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects

Mohammed Alamoudi
University of Miami, al3amodi@hotmail.com

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UNIVERSITY OF MIAMI

INVESTIGATION AND ANALYSIS OF THE EFFECTS OF MANUAL LIFTING AND CARRYING ACTIVITIES ON POSTURAL AND GAIT STABILITY IN NORMAL SUBJECTS

By

Mohammed Alamoudi

A DISSERTATION

Submitted to the Faculty
of the University of Miami
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INVESTIGATION AND ANALYSIS OF THE EFFECTS OF MANUAL LIFTING AND CARRYING ACTIVITIES ON POSTURAL AND GAIT STABILITY IN NORMAL SUBJECTS

Mohammed Alamoudi

Approved:

Shihab Asfour, Ph.D.
Associate Dean of Engineering
Professor of Industrial Engineering

Francesco Travascio, Ph.D.
Assistant Professor of Industrial Engineering

Moataz Eltoukhy, Ph.D.
Assistant Professor of Kinesiology and Sport Sciences

Mohamed Fahmy, Ph.D.
Lecturer of Industrial Engineering

Arzu Onar-Thomas, Ph.D.
Associate Member
St. Jude Children's Research Hospital
Memphis, Tennessee

Guillermo Prado, Ph.D.
Dean of Graduate School

ALAMOUDI, MOHAMMED (Ph.D., Industrial Engineering)

Investigation and Analysis of the Effects
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Manual material handling (MMH) contributes to a large percentage of musculoskeletal disorders. Examples of its fundamental activities are lifting and carrying tasks that can be accomplished in several strategies, with each one imposing different types of stresses on the musculoskeletal system. These types of stresses may perturb the stability of the human body and may cause falls. Therefore, the goal of this study was to investigate the effect of MMH tasks on postural and locomotion stability using motion capturing system. Postural and dynamic stability were measured using new stability measures that were introduced in this study. A point inside the BoS, which represents the optimal location of stability (i.e. CBoS), was the reference point for quantifying stability. Postural stability was measured by finding the deviation of the body's CoM from the CBoS. Using the proposed measures, the effect of lifting task on postural stability was investigated. Eight subjects lifted 25, 35 and 45 lbs. box to 30" and 60" shelf heights. Manual material lifting of heavy weights significantly destabilized the human body in both directions. Moreover, the heights of the working surfaces that force the body to be changed from the upright gesture exacerbated the effect on postural stability. Therefore, it is recommended that, whenever possible, the working surface during lifting tasks to be at elbow height in order to keep the upright posture of the human body. In addition, this study adds to the knowledge used for designing manual material carrying tasks from the perspective of locomotion stability, gait measures and loads at the lumbar spine. Gait stability was measured by finding the deviation between the CBoS and the CoM extrapolated with its velocity. Thirty participants carried 10 and 30 lbs loads via frontal, lateral, bilateral, and posterior carriages. Frontal and lateral methods generated the most unstable conditions compared to the others. The unstable locomotion forced the gait parameters to be significantly altered in order to maintain stability. Additionally, the postures maintained in these conditions resulted in significantly high compression, shear forces, and flexion/ extension and lateral moments acting at the L5/S1 disc when compared to the other carrying methods. Moreover, heavier weights exacerbated the effect on the dependent variables. Notably, bilateral and posterior carrying methods provided results comparable to the unloaded walking baseline. In conclusion, to reduce the potential risks associated with load carrying, the recommendation to split the load between both hands or carrying it posteriorly should be taken into account while designing MMH activities.

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LIST OF ABBREVIATION

A/P: Anterior-posterior direction.

BoS: Base of support.

CBoS: Center of base of support.

CoM: Body’s center of mass.

DS: Double support phase.

L5/S1: The intervertebral disc between the fifth lumbar and first sacrum vertebrae.

M/L: Medio-lateral direction.

SS: Single support phase.

XCoM: Extrapolated center of mass.

CHAPTER 1: INTRODUCTION

Second only to motor vehicle accidents, slip and fall accidents account for 15% of all accidental deaths in the United States, where 60% these accidents occurred at the workplace. Moreover, 5% of these incidents resulted in fractured bones, which is the most common injury. Loss of balance incidents are considered an economic burden to the US economy. They are the primary cause of lost time at work, where 22% of falls result in more than 31 days of missed work (U.S. Department of Labor, 2013). According to (Parsons, Pizatella, & Collins, 1986) 15% of the total loss of stability incidents occurred because of static manual material handling (MMH) activities, such as lifting, lowering and holding. Moreover, dynamic MMH activities, such as load carrying, are recognized as the first primary occupational factor contributing to loss of balance, resulting in over 30% of the total fall injures.

The maintenance of stability is a complex task that requires the interaction between the sensory, nervous, and motor systems (Duarte & Freitas, 2010). Sensory system delivers information regarding the position of body segments in relation to other segments and to the environment. Central nervous system receives the information delivered by the sensory system, and then sends nervous impulses to the muscles (i.e. motor system) to ensure that the vertical projection of the body's center of mass (CoM) is regulated in an efficient and accurate way (Duarte & Freitas, 2010). In addition, the motor system stability component entails the spine that can withstand different types of forces to provide the skeletal system with the support it needs to maintain ideal posture, both statically and dynamically, in all planes of motion.

Three factors affect the control of stability. Namely, environmental, task-related, and personal factors (Hsiao & Simeonov, 2001). Environmental factors involve the information available from visual interaction, such as moving visual scenes, depth perception, and physical interactions, such as restricted area, and material properties of support surfaces. Task-related factors include load handling, physical exertion, fatigue, and complexity of tasks (Nevitt, Cummings, Kidd, & Black, 1989; Tinetti, Speechley, & Ginter, 1988). Personal factors include individual differences. In this study the task related, and the personal factors were investigated.

An example of task-related factor that affects body stability is MMH tasks. In the industrial fields there are different tasks that require frequent lifting, holding and carrying loads with different body postures. Maintaining stability becomes more challenging when it is coupled with MMH activities, since the load carried alters the location of the CoM. Consequently, the human body adopts compensation strategies, such as alterations of gait patterns or trunk adjustments. All these changes may compromise the static and dynamic stability, potentially leading to fall, and increase the mechanical load on the lower back, which may lead to disc degeneration (Iatridis & ap Gwynn, 2004)

The major component that plays an important role in body stability is the CoM. The human body is considered unstable when its CoM lies at or close to the boarders of the BoS. However, existing measures quantify stability by finding the trajectories or the velocity of the CoM during a certain activity, regardless of its closeness to the edges of the BoS. According to (Whiting & Rugg, 2006) stability is optimal when the CoM is closer to the centroid of the base of support (CBoS). Therefore, in this study postural stability was measured by calculating the deviation between CoM and CBoS. The same concept was used in measuring locomotion stability. However, the CoM was extrapolated with its velocity to find the extrapolated center of mass (XCoM) (A. Hof, Gazendam, & Sinke, 2005).The choice of using XCoS in place of the CoM is motivated by the fact that the direction of the velocity of a system plays a fundamental role in stability: even when the CoM falls within the BoS, a system may be unstable if the velocity is directed outward the CBoS; diametrically, stability can be achieved even if the CoM is outside the BoS, as long as the velocity is directed towards the CBoS.

To date, few studies have analyzed the effect of weight lifting on postural stability. However, none of them examined the effect of shelf heights on postural stability. For instance, (Jiahong, Xingda, & Chun-Hsien, 2015) investigated the effect of asymmetric and symmetric lifting of different loads on postural stability. One shelf was placed in the sagittal plane (i.e. symmetric), and the other one was placed at 60° to the right of the sagittal plane (i.e. asymmetric). It was found that in order to maintain postural stability during lifting, asymmetric lifting should be avoided if possible. Additionally, (Kollmitzer, Oddsson, Ebenbichler, Giphart, & DeLuca, 2002) investigated the effect of load lifting with different base of support configurations. Base of support was varied between parallel and step stance. No difference was observed between them in terms of postural stability. Therefore, one of the goals of this study was to investigate the effect of different load lifting to different shelf heights.

A few studies have investigated walking stability while carrying loads in the form of back packs (Qu, 2013) or double pack (Liu, Lockhart, & Granata, 2007) in order to simulate military occupational activities. Additionally, (Holbein & Redfern, 1994) compared walking stability in the medial-lateral direction while carrying loads in different strategies. Similarly, compression and shear forces on the lower back while carrying a load in one hand or splitting it between both hands have been measured (Rose, Mendel, & Marras, 2013). Also, shear force acting on the lumbar spine have been measured only for the cases of frontal, lateral and posterior carriages (Rose et al., 2013). Therefore, one of the objectives of this study was to further elucidate the effects of magnitude and method of load carrying on both walking stability and spine biomechanics. This was done by conducting a motion capture analysis to yield, for any experimental condition examined, gait stability and spatio-temporal parameters, and forces acting on the lumbar spine.

Objectives

The main goal of this dissertation is to cover all aspects of stability. Namely, postural and gait stability. Postural stability is the ability to maintain the body's center of mass (CoM) within the boarder of the base of support (BoS). The goals regarding analyzing postural stability in this study are:

- To introduce postural stability measures that can measure body stability more reliably and accurately.
- To investigate the effect of load lifting with shelves heights on postural stability.

Gait stability is the capability to keep the body balanced and to maintain coordination of body segments while walking. The goals regarding investigating gait stability in this study are:

- To investigate the effect of manual load carrying on gait stability, because the ability to preserve stability during walking might be challenged by the control of perturbations from load carrying.
- To understand how the human body will be adapted to sustain stability, since manual load carrying induces perturbations to gait stability.
- To analyze the effect of load carrying with different postures on lumbar spine kinematics and kinetics.

Hypothesis

Effect of Load Lifting on Postural Stability

It was hypothesized that the new measures will quantify postural stability more reliably and accurately, since they are the only measures that measure stability based on a reference point on the BoS. Moreover, it was hypothesized that placing loads on shelves at elbow level is better than the ones at knee level.

Effect of Load Carrying on Gait Stability

It was hypothesized that the heavier the load being carried, the less stable is the gait. Additionally, it was hypothesized that balancing the load between both hands will have less effect on gait stability than carrying using one hand. Moreover, it was hypothesized that posterior carrying will have less effect on gait stability than anterior carrying, because the weight carried in the backpack is closer to the body's CoM. Furthermore, it is hypothesized that the more effect on gait stability (i.e. less stable), the more effects will be on gait spatio-temporal parameters, trunk kinetics and kinematics, because the body will try stabilize itself and prevent falling.

CHAPTER 2: LITERATURE REVIEW

Postural Stability

The classical definition of the postural stability is based upon the global CoM or CoP position and its displacement within the base of support (Blaszczyk, Lowe, & Hansen, 1994). Therefore, the movement of the CoM or CoP is the variable that actually causes the sway of the whole body. The components in the Anterior-Posterior (A/P) and Medio-Lateral (M/L) directions are the components of interest in studying postural stability. Several measures are used to measure body sway from of the CoM trajectories. Some of the measures are computed separately for each direction (i.e. the A/P or M/L), such as the excursion of the CoM, and sway velocity. Moreover, other measures are computed in both directions simultaneously, such as the average sway length, and mean displacement velocity. These measures have been widely used in occupational safety research (Bhattacharya, Succop, Kincl, Lu, & Bagchee, 2002; Liu, Zhang, & Lockhart, 2012; Raymakers, Samson, & Verhaar, 2005; Simeonov, Hsiao, Dotson, & Ammons, 2003; Wade, Garner, Redfern, Andres, & Roche, 2011). The major drawback of postural stability measures is lack of reliable and sensitive sway measures that could be used for the evaluation of postural stability (Baloh, Jacobson, Enrietto, Corona, & Honrubia, 1998).

Force platform posturography is a commonly used method for quantifying balance performance. Various parameters derived from the center of pressure (COP) signal provide different types of information on postural control mechanisms (Palmieri, Ingersoll, Stone, & Krause, 2002). Numerous studies have used a variety of COP measures to detect between group differences (Baloh et al., 1994; Era & Heikkinen, 1985), predict falling risk (Bergland & Wyller, 2004; Maki, Holliday, & Topper, 1994; Pajala et al., 2008; Piirtola & Era, 2006), and evaluate the efficacy of balance training programs (Crilly, Willems, Trenholm, Hayes, & Delaquerrière-Richardson, 1989; Judge, Lindsey, Underwood, & Winsemius, 1993). Center of pressure (COP) is the most common and is defined as the point of application of the ground reaction forces under the feet. CoP is the outcome of the inertial forces of the body and restoring equilibrium forces of the postural control system. COP displacement can be characterized as 1- and 2-dimensional measures. These measures include but are not limited to; the root mean-square error (RMS), CoP range, mean CoP position, sway area, mean CoP velocity, and CoP path length (Lafond, Corriveau, Hébert, & Prince, 2004). COP measures are subject to measurement errors with three potential sources: instrument, observer (i.e. variability in procedure adopted) and variability in biologic phenomena being measured. An essential part of COP variability has been attributed to the intrinsic variability of the postural control system since the precision of instrument and procedure was satisfactory in numerous studies. Although high level of reliability cannot guarantee the validity of a measure, identifying the measurement error as a prerequisite for discriminative and evaluative purposes is a major concern for clinicians when they use COP parameters. Like many biologic measurements, COP has an intrinsic variability that affects the reliability and the validity of postural control outcomes. Assuming that the measurement conditions are constant, the difference between 2 measures is attributable to the error variance, which is influenced by the variability of the phenomena measured and the precision of the instrumentation. Increasing the number of repetitions decreases the weight of the error variance compared with the true score.

Gait Stability

Standing stability is generally defined in static terms, based on the relationship between a person's CoM and the BoS. As long as the projection of the CoM remains within the horizontal bounds of the BoS, one remains stable. This definition cannot, however, be properly applied to walking, or even standing, as it does not take into account the horizontal velocity of the CoM (Pai & Patton, 1997). To address this limitation, (A. Hof et al., 2005) proposed a new measure referred to as the 'margin of dynamic stability' (MDS) which can more appropriately be applied to dynamic tasks like walking. The MDS is defined as the distance between the velocities adjusted or 'extrapolated' position of the CoM (XCoM) and the edge of an individual's BoS at the double support phase. This definition of stability suggests that foot placement could be used to control MDS magnitude during walking (A. L. Hof, 2008). Thus, one potential goal of walking may be to maintain some minimum MDS in the A/P direction and maximum MDS in the M/L direction. (Rosenblatt & Grabiner, 2010) showed that average lateral MDS did not change significantly between overground and treadmill walking in healthy subjects, although step width did. This supports the idea that foot placement during walking could be chosen to achieve a constant lateral MDS. Similarly, (MacLellan & Patla, 2006)found no difference in average MDS in the M/L direction on rigid versus compliant surfaces. However, they did find a difference in the average A/P MDS. Maintenance of average lateral MDS was also observed in amputees walking on irregular surfaces (Curtze, Hof, Otten, & Postema, 2010). These results suggest that individuals may use foot placement to control lateral stability during walking and that this control is independent of walking surface. However, these studies quantified only average MDS.

Mean MDS cannot indicate how an individual recovered from any single step because it only quantifies an individual's overall, average stability over an entire series of steps.

Contribution of Gait Parameters in Gait Stability

At any given walking speed it is possible to select different combinations of stride frequency and stride length, but again individuals tend to choose a specific stride frequency and length consistently (Kuo, 2001). Fallers and fall-prone people often walk slower, with shorter steps and a lower step frequency than non-fallers (Vivian Weerdesteyn PhD, de Niet MSc, van Duijnhoven MSc, & Geurts, 2008; von Schroeder, Coutts, Lyden, & Nickel, 1995). These differences in gait pattern, in particular the lower walking speed, are often explained as strategies to decrease fall risk (Dingwell & Marin, 2006; England & Granata, 2007). To investigate whether gait pattern selection or adaptations could serve the purpose of decreasing fall risk, several studies have examined responses to balance perturbations during gait (Hak et al., 2012; Hak, van Dieën, et al., 2013; Kang & Dingwell, 2008). Evidence was found that able-bodied people, but also people with a transtibial prosthesis, effectively deal with perturbations by increasing their stride frequency and decreasing their stride length, while keeping walking speed constant. These results suggest that instead of a decrease in walking speed, an increase in stride frequency and a decrease in stride length are adopted to minimize the risk of falling. (Hak, Houdijk, Beek, & van Dieen, 2013) investigate whether adaptations of stride length, stride frequency, and walking speed, independently influence the size of the M/L and A/P margins of stability (MDS) during walking. Participants walked on a treadmill at different combination of stride frequency, stride length, and consequently at different walking speeds. Generalized Estimating Equations were used to investigate the independent contribution of stride length, stride frequency, and walking speed on the measures of gait stability. Increasing stride frequency was found to enhance M/L margins of stability. However, A/P margins of stability became larger as stride length decreased or walking speed increased.

Effect of Load Carrying on Gait Stability

Few studies investigated the effect of load carrying on gait stability. Moreover, most of these studies examined the effect of carrying loads that were attached to subjects' bodies, such as backpack, or load vest on gait stability, except one study that was conducted by (Holbein & Redfern, 1994) who investigated the effect of carrying a load with different carrying strategies on walking. Six carrying strategies were tested in this study. Namely, symmetrical carrying by two hands at knuckle level, symmetrical carrying by two hands at waist level, asymmetrical carrying at knuckle level, asymmetrical carrying at waist level, asymmetrical carrying at shoulder level, and unladen condition. The dependent variable was the M/L displacements of the body and load CoM from the path of the progression. The path of progression was defined as a straight line from the mid-ankles at the beginning and the end of a stride. Carrying asymmetrically always resulted in significantly larger CoM M/L. it was found that the posture and load conditions and their interaction significantly affected the CoM M/L displacement. Further analysis showed that the various postures resulted in CoM M/L responses from the greatest to smallest magnitudes in the following order: 1-hand-high, 1- hand-at-waist, 1-hand-at-side, 2-hands-at-side, and 2- hands-at-waist. (Qu, 2013) examined the effect of physical and cognitive effects on gait stability. Subjects walked on a treadmill while carrying a backpack that was set to 0 kg, 8.5 kg, and 20 kg. Only physical load had a significant effect on gait stability, especially in the M/L direction. It was found that the heavier the load being carried, the less stable is the gait. Moreover, (Liu & Lockhart, 2013) studied the effect of wearing a load vest that weighed 12.7 kg on walking stability. It was found that load carrying tasks were associated with declined walking stability, which may increase the risk of falling.

Effect of Load Carrying on Spinal Stresses

When the spine takes high stress, stress fractures occur. It most commonly occur in the lower back, especially in the fifth lumbar vertebra (Jacobs & Golmohammad, 2003). Stress fractures can weaken the vertebra so much that it shifts out of its proper position. The bones may press on the nerves, resulting in pain, and numbness. In more severe cases, surgical intervention may be needed to correct this problem (Granata, Marras, & Davis, 1997). Stress fractures are most common among who put a significant amount of stress on the lower back, such as workers who perform manual material handling at their workplaces, such as lifting and carrying different loads in the industrial fields, as shown in Figure 1 (Group, 1994). Lifting tasks develop compression and tension in the vertebral column. Load characteristics (weight, size, shape, handles, other couplings), and Posture / handling techniques (stretching, reaching, twisting) are common factors for spinal stresses. Between 85-95% of all disc herniation occur at the L4/L5 and L5/S1 levels, because L5/S1 has the potential to incur the greatest moment and of the most vulnerable tissues to forced-induced injuries (C. K. Anderson & Chaffin, 1986) .Therefore, Back compression is a good predictor of stress and overexertion (Jensen, 1980).

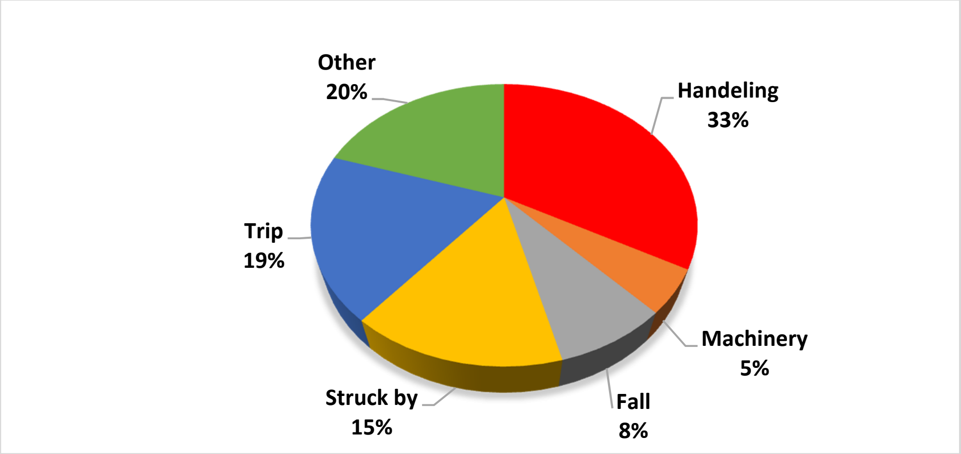


Figure 1. Spine injuries at the workplace.

Moreover, (D. Chow, Li, Lai, & Pope, 2011) investigate the effect of different load carriage methods on spinal loading over time via the measurement of spinal compression. They were asked to carry a load equivalent to 15% of their body weight either anteriorly or posteriorly for 20 min followed by 10 min of unloading. Their statures were measured before load carriage and every 2 min after carrying the load. The amount of spinal compression was found to be associated with the duration of carrying. Spinal compression during anterior carriage was larger than posterior carriage. Moreover, (Al-Khabbaz, Shimada, & Hasegawa, 2008) analyzed trunk-lower extremity muscle activities and trunk postural changes during the carriage of different backpacks. Four standing modes were studied in the experiment: unloaded standing, 10% body weight (BW) load (in the form of a backpack), 15% BW load, and 20% BW load. Bilateral rectus abdominis, erector spinae, vastus medialis and biceps femoris muscle activities were recorded using surface electromyography (EMG), while trunk inclination, side flexion and rotation were measured by using motion capturing system during all standing modes. The results showed that rectus abdominis muscle activities increased progressively as the backpack load increased. As for the trunk posture, almost the same backward inclination was adapted even with increasing backpack heaviness. Twenty percent BW backpack causes the most significant muscular and postural changes so it should be avoided. In addition, Chow (D. H. Chow et al., 2006) examined the effects of backpack load on the posture and balance of schoolgirls with AIS and normal controls. Standing posture were recorded without a backpack and while carrying a standard dual-strap backpack loaded at 7.5%, 10%, 12.5% and 15% of the subject's bodyweight (BW). Kinematics of the pelvis, trunk and head were recorded using a motion analysis system and center of pressure (COP) data were recorded using a force plate. Increasing backpack load causes a significantly increased flexion of the trunk in relation to the pelvis and extension of the head in relation to the trunk, as well as increased A/P range of COP motion. While backpack load appears to affect balance largely in the A/P direction, differences between groups were more evident in the M/L direction. Additionally, (D. Chow, Leung, & Holmes, 2007) analyzed spinal curvature and proprioception (in terms of spinal repositioning consistency) of 15 schoolboys during normal upright stance without a backpack and while carrying a specially adapted backpack loaded at 10, 15 and 20% of their bodyweight were measured and compared. A significant flattening of the lumbar lordosis and the upper thoracic kyphosis was found with increasing backpack load, as well as a significant decrease in the thoraco-lumbar and lumbar repositioning consistencies. Carriage of a loaded backpack causes immediate changes in spinal curvature and appears to have a direct effect on the repositioning consistency. (Rose et al., 2013) assessed the lumbar spine loads of 16 subjects as they assumed six styles of carrying (backpack, bin with handles, bin supported underneath, briefcase, cross shoulder, and straight shoulder) at two weight levels (12.5 lbs, and 25 lbs) and two activity levels(walking, and standing). Most carrying methods in the trials resulted in relatively low levels of spine loading. Anterior/posterior (A/P) shear loading was the only spine-loading dimension that reached biomechanically meaningful levels. Two carrying conditions, with bins carried in front of the body, significantly increased A/P shear compared with other carrying styles. This increase appeared to be due to the greater moment arms occurring in these conditions. Many of the other carrying styles produced A/P shears that were similar to those observed when carrying nothing at all. The backpack carry characteristically produced especially low spine loads. The findings of the study suggest that to achieve optimal carrying in terms of spine loading, loads should be positioned close to the body, even when carrying relatively light loads. (Singh & Koh, 2009) investigated the impact of backpack load carriage and its vertical position on the back on temporal–spatial and kinematic parameters associated with gait and postural stability for static and dynamic conditions. For dynamic conditions, the participants walked on an instrumented treadmill with 10%, 15% and 20% bodyweight (BW) loads on two locations on the back. Walking velocity, cadence, and double support time for 20% load condition were significantly different compared to the unloaded condition indicating that gait changes may have occurred to minimize gait destabilization. (Korovessis, Koureas, Zacharatos, & Papazisis, 2005) investigated the influence of backpack carrying on spinal profile shoulder and trunk. A randomly selected sample of 1263 students aged 12–18 years were asked for dorsal (DP) and low back pain (LBP) during the school period and holidays. Debrunner’s Kyphometer and Scoliometer were used to measure craniocervical angle (CCA), thoracic kyphosis, lumbar lordosis, and shoulder shift (BL).

Upper trunk shift from plumb line were recorded. Girls suffer from DP more often and of much more intensity pain than boys in school period and in holidays. Backpack carrying decreased CCA and changed shoulder and upper trunk shift. Asymmetrically backpack carrying increased DP and LBP. (Motmans, Tomlow, & Vissers, 2006) investigated the effect of load carrying on spinal muscles. It was shown that backpack carriage significantly increased trunk flexion with flattened lumbar spine and increased extension in cervical spine. Moreover, (D. Chow et al., 2007) studied the load carrying effect on spinal motor control. Spinal repositioning ability was also affected by backpack carriage and the effects were found to be dependent on the amount of the load carried.

CHAPTER 3: METHODOLOGY

Center of Mass (CoM) Determination

When a body is acted upon by gravity, all of the mass particles of the body experience a force of attraction directed toward the ground. The resultant force of all of these forces is the body's weight and the location at which the resultant force is assumed to act is the center of gravity (CoG). Moreover, the CoG or CoM is the location at which all of the body's weight is assumed to be concentrated and is the point that depicts the general motion of the entire body. Because the CoM of a body is dependent on the distribution of its mass, the CoM location for a rigid body will be fixed. However, the CoM of a body whose mass distribution can be altered (i.e., the human body) will not have a fixed location. Two methods have been traditionally used to assess CoM location. Namely, a reaction board technique which is easily applied to static positions, and a segmentation method, the more versatile of the two since it can be applied to dynamic and static situations, which involves an estimation of individual segment masses and positions. It is also known as the kinematic method, which is similar to the weighted average position of the segments (Corriveau, Hébert, Prince, & Raîche, 2000; Helene Corriveau et al., 2000; Hasan et al., 1996). The segmentation method is based on a simple principle that states that the sum of the moments of the individual body segments defined relative to an arbitrary axis must equal the moment of the sum (i.e., the moment of the total body mass) relative to the same axis:

$$X_{CoM} = \frac{\sum w_i x_i}{W}$$

$$y_{CoM} = \frac{\sum w_i y_i}{W}$$

Where,

X_{CoM} : The coordinate of the CoM on the x-axis.

w_i: The weight of segment i.

x_i: The coordinate of the CoM of segment i on the x-axis.

W: Total body weight

y_{CoM}: The coordinate of the CoM on the y-axis.

y_i: The coordinate of the CoM of segment i on the y-axis.

The accuracy of the CoM location is related to the mass inertia parameters (MIP) providing the CoM position and mass fraction of each segment of the model (Zatsiorsky, Seluyanov, & Chugunova, 1990). The Zatsiorsky-Seluyanov's MIP were used to estimate the CoM location. Table 1, summarize the mass inertia parameters for each segment. The skeletal anthropometric points are shown in Figure 2.

Table 1. Adjusted Zatsiorsky-Seluyanov's segment mass inertia parameters (MIP).

Segment	CoM Location (% length)		Segment Mass (% from total body mass)	
	Male	Female	Male	Female
Head	59.8% from vertex	48.4% from vertex	6.94%	6.68%
Trunk	44.9% from suprasternal	49.6% from suprasternal	43.46%	42.57%
Upper arm	57.7% from shoulder	57.5% from shoulder	5.42%	2.55%
Forearm	45.7% from elbow	45.7% from elbow	3.24%	1.38%
Hand	79% from wrist	74.7% from wrist	1.22%	0.56%
Thigh	41% from hip	36.1% from hip	28.32%	14.78%
Shank	44.6% from knee	43.9% from knee	8.66%	4.81%
Foot	44.2% from heel	40.1% from heel	2.74%	1.29%

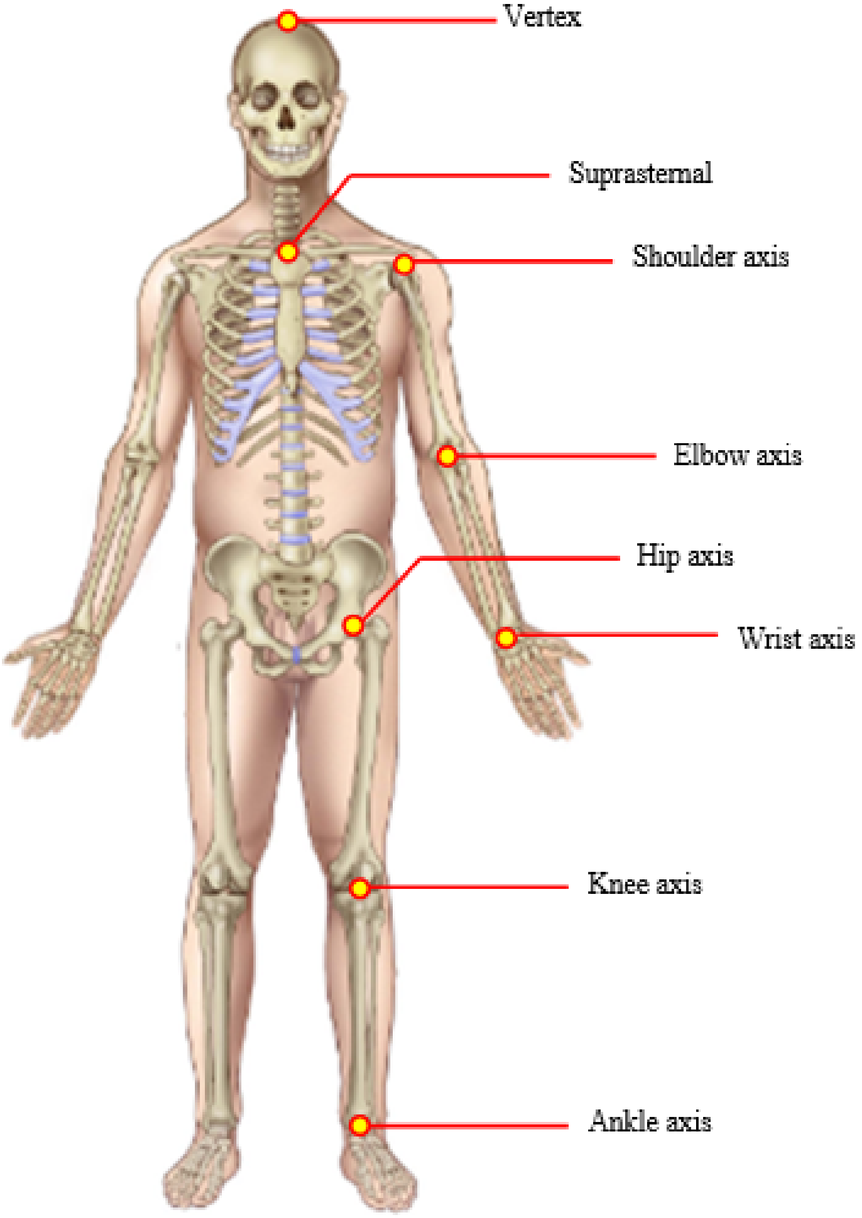


Figure 2. Skeletal anthropometric points.

Motion Capture System

The experiments were all conducted at the Biomechanics Lab located at the University of Miami. The lab incorporates a Vicon Motion Capture System (Oxford Metrics). It integrates and synchronizes with four force plates, and ten MX cameras. The cameras provide 1024 x 1024 pixel resolution and frame rates up to 250 Hz. The high camera resolution allows for larger capture volume, more accurate and multiple viewing angles, and fewer gaps in trajectories. Each Kistler force plate consists of a top plate with four 3-component force piezoelectric sensors. The Lab is equipped with four Kistler force plates, three of are 60x40 cm and the fourth is 90x60 cm. The output charge of the force plates is amplified and converted to a voltage, using a charge amplifier. The setup including the force plates and the MX cameras is shown in Figure 3.

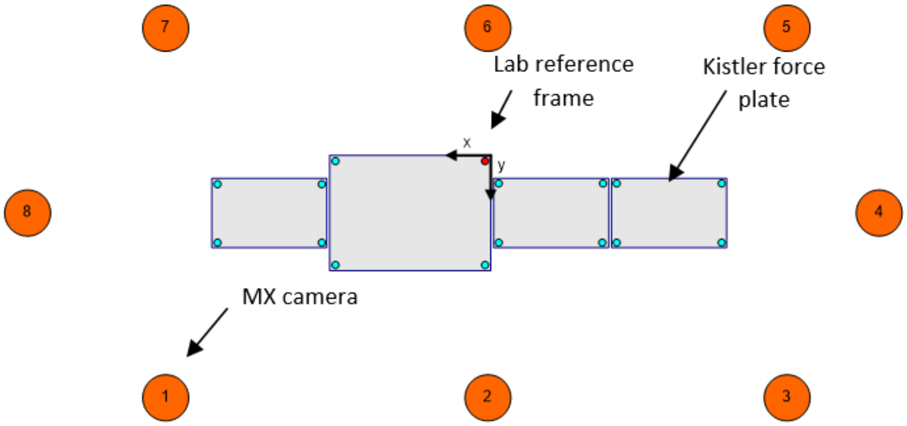


Figure 3. Forceplates and camera configuration.

The accuracy of the data collected through Vicon system depends on the calibration process. The calibration accounts for the camera position, orientation, focal length, image distortion etc. The calibration process is executed in two stages, static and dynamic. Both processes help reconstruct the three dimensional motion in the workstation. While the static calibration is used to define the origin and direction of the X, Y, and Z axes. The dynamic stage of the calibration is conducted in order to verify the visibility of the markers from all the cameras.

A number of anthropometric measurements are collected, such as height, weight, leg length (hip to ankle), shoulder offset, elbow width, wrist width, knee and ankle widths will be collected. Once the subject is ready to start the experiment, the markers were placed on their body according to the Plug-In Gait model. Markers' labels and placements are shown in Table 2. In order to capture the actual area of contact between both feet and the ground, 2 extra markers were attached on the left and right 5th metatarsal, as shown in Figure 4.

Table 2. Markers' labels and description.

	Marker	Description
Upper Body	RFHD & LFHD	Placed over the left/ right forehead
	LBHD & RBHD	Placed over the left/ right back of the head
	CLAV	Placed between the two collar bones and below the base of the neck
	STRN	Placed over the base of the middle of the ribcage
	C7	Located along the spinal column right where the back of the neck ends
	T10	Placed over the 10th thoracic vertebrae (10 vertebrae after the C7)
	RBAK	Placed below the right shoulder marker
	LSHO & RSHO	Placed over the left/ right shoulder
	LUPA & RUPA	Placed over the upper arm between the shoulder and the elbow.
	LELB & RELB	Placed over the left/ right elbow
	LWRA & RWRA	Placed over the anterior side of the left/ right wrist joint
	LWRB & RWRB	Placed over the posterior side of the left/ right wrist joint
	LFIN & RFIN	Placed over the left/ right fingers.
Lower Body	LASI & RASI	Placed over the left/ right anterior superior iliac spine.
	LPSI & RPSI	Placed over the left/ right posterior superior iliac spine at the point where the spine joins the pelvis.
	LKNE & RKNE	Placed on the lateral epicondyle of the left/ right knee.
	LTHI & RTHI	Go over the surface of the left/ right thigh.
	LANK & RANK	Placed on the left/ right ankle.
	LTIB & RTIB	Placed on between the knee and ankle markers
	LTOE & RTOE	Go over the second metatarsal head
	LHEE & RHEE	Placed on the heel at the same height
	L5MT & R5MT	Placed on the left and right 5th metatarsal

All markers are shown in figure 4.

Afterwards, all subjects are asked to perform the static trial by standing barefoot in the experimental area for several seconds while data is being recorded. Markers are then labeled manually in one trail so that the subsequent trials can be labeled automatically.

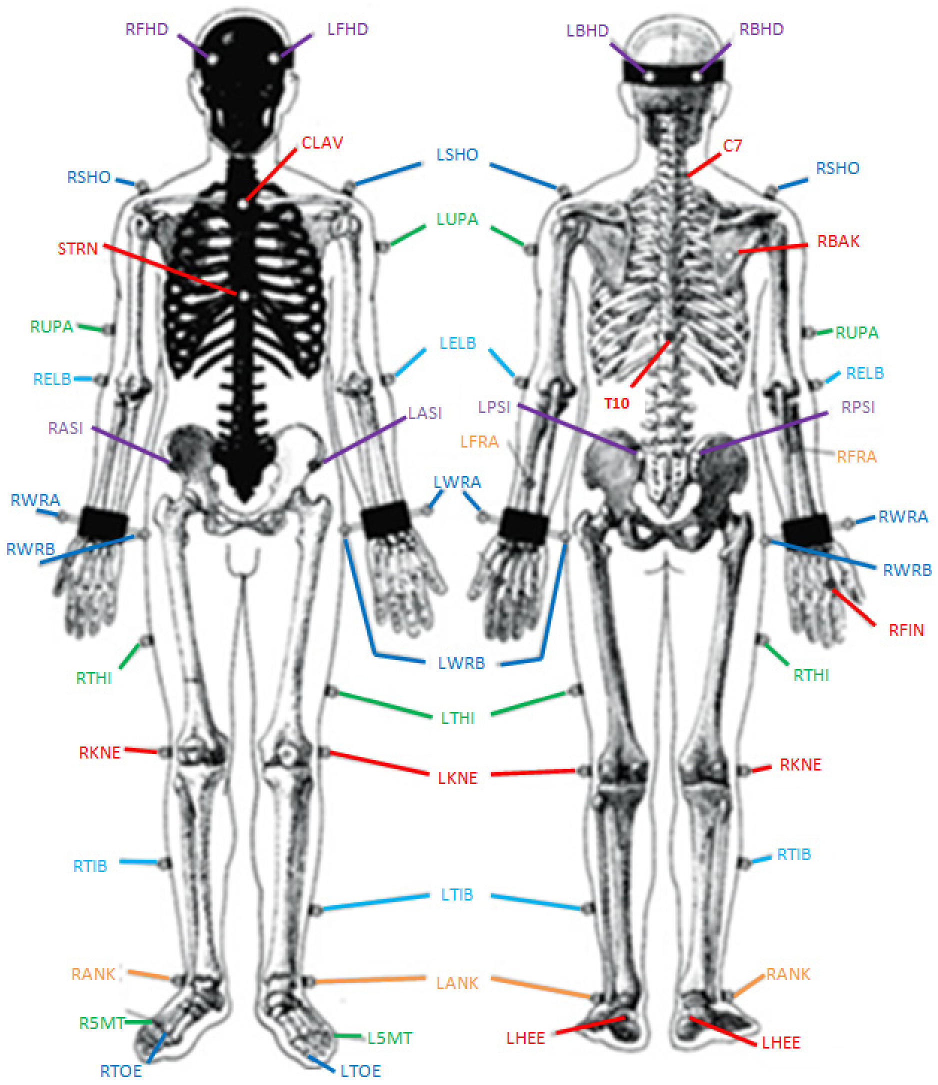


Figure 4. Plug-in-gait model markers placement.

Postural Stability Measures

Existing Measures

There are several measures that are commonly used in stability studies. Namely, excursion of CoM, which is the distance between the maximum and minimum CoM displacement in the A/P (eq. 1), and M/L directions (eq. 2). Moreover, CoM velocity, which determines how fast the CoM is moving in the A/P (eq. 3), and M/L directions (eq. 4). Additionally, average sway length, which is the average distance traveled by the CoM in both directions (eq. 5). In addition, mean displacement velocity, which is the displacement of the CoM in both direction per unit time (eq. 6). These measures have been widely used in occupational safety research (Bhattacharya et al., 2002; Liu et al., 2012; Raymakers et al., 2005; Wade et al., 2011). The equations are as follow,

$$\text{A/P Excursion (mm)} = |y_{max} - y_{min}| \ldots eq. 1$$

$$\text{M/L Excursion (mm)} = |x_{max} - x_{min}| \ldots eq. 2$$

$$\text{A/P Velocity (mm/sec)} = \frac{1}{T}\sum_{i=1}^{N} |y_i - y_{i-1}| \ldots eq. 3$$

$$\text{M/L Velocity (mm/sec)} = \frac{1}{T}\sum_{i=1}^{N} |x_i - x_{i-1}| \ldots eq. 4$$

$$\text{Average Sway Length (mm)} = \frac{\sum_{i=1}^{N}\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{N} \ldots eq. 5$$

$$\text{Mean Displacement Velocity (mm/sec)} = \frac{\sum_{i=1}^{N}\frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{t_i - t_{i-1}}}{N} \ldots eq. 6$$

Where,

y_{max}: Maximum position of CoM in the y-axis

y_{min}: Minimum position of CoM in the y-axis

x_{max}: Maximum position of CoM in the x-axis

y_i: Location of CoM in the y-axis at frame i

x_i: Location of CoM in the x-axis at frame i

T: Total time of the trial

t_i: Time at frame i

N: Number of frames

Proposed Postural Stability Measures: Deviation of CoM from CBoS

Based on our knowledge, none of the existing stability measures that are commonly used in stability research evaluate stability based on a point in the BoS that has the least sway. Therefore, the main goal of this paper is to introduce new stability measures that measure stability based on a point where the optimal stability locates. When the CoM of a human body lies at or near the CBoS, it is more stable than when it lies far from it or near the edge of the BoS (Whiting & Rugg, 2006). Therefore, the CBoS is considered the reference point where the optimal stability is. Three new measures calculate stability by measuring the deviation or the distance from the CoM to the CBoS, as shown below. Equation 7 measures stability by finding the absolute value of the difference between the location of the CoM to the CBoS in the A/P (or fore-aft) direction. Equation 8 does the same but in the M/L (or sideways) direction. Equation 9 measures the actual distance between the CoM and the CBoS by calculating the square root of the summation of the deviation in each directions squared. The equations are as follow,

$$A/P\ \ Dev_i\,(mm) = \left|CBoS_{AP_i} - CoM_{AP_i}\right| \dots eq.7$$

$$M/L\ Dev_i(mm) = \left|CBoS_{ML_i} - CoM_{ML_i}\right| \dots eq.8$$

$$Total\ Dev_i(mm) = \sqrt{A/P\ \ Dev_i^2 + M/L\ Dev_i^2} \dots eq.9$$

Where,

$A/P\ \ Dev_i$: The deviation of the CoM from CBoS in the fore-aft direction at frame i

$CBoS_{AP_i}$: The component of the CBoS in the fore-aft direction at frame i

CoM_{AP_i}: The component of the CoM in the fore-aft direction at frame i

$M/L\ Dev_i$: The deviation of the CoM from CBoS in the sideways direction at frame i

$CBoS_{ML_i}$: The component of the CBoS in the sideways direction at frame i

CoM_{ML_i}: The component of the CoM in the sideways direction at frame i

$Total\ Dev_i$: The total deviation of the CoM from the CBoS at frame i

The previous formulas measure stability at each frame. Therefore, at the end of a trial of an experiment, these values should be averaged by dividing it by the number of frames in order to get a value that represents the stability for that trial. The graphical illustration of the proposed equation is shown in Figure 5. The most important part in the previous equations is to find the location of the CBoS accurately. The reflective markers of the feet (or BoS) will create a convex polygon, which all its interior angles are less than 180°. The code will divide the n-sided polygon into a set of (n-2) triangles for which the area and centroid will be calculated. The area of each triangle will be calculated by Heron's formula, as seen below

$$Area = \sqrt{S(S-a)(S-b)(S-c)}$$

$$S = \frac{a+b+c}{2}$$

Where, *a, b,* and *c* are the triangle sides

After calculating the area of each triangle, the code will find the center of each one by the following formulas.

$$x_{cen} = \frac{x_1 + x_2 + x_3}{3}$$

$$y_{cen} = \frac{y_1 + y_2 + y_3}{3}$$

Where, $[x_1, y_1]$, $[x_2, y_2]$, and $[x_3, y_3]$ are a triangle corners.

Then, in order to find the center of a polygon (which is a set of triangles) the code will use the following formulas.

$$x = \frac{\sum(x_{cen_i} * Area_i)}{\sum Area_i}$$

$$y = \frac{\sum(y_{cen_i} * Area_i)}{\sum Area_i}$$

Moreover, postural stability in the A/P and M/L directions were measured as the normalized distance of the deviation of the CoM with respect to the vertical and horizontal distance between the CBoS and the edge of the BoS, respectively, as shown in Figure 5.

$$Postural\ Stability\ (A/P) = \frac{A/P\ Dev}{V} \times 100\%$$

$$Postural\ Stability\ (M/L) = \frac{M/L\ Dev}{H} \times 100\%$$

Where,

$A/P\ Dev$: The deviation of the CoM from CBoS in the fore-aft direction.

V: The vertical distance between the CBoS and the edge of the BoS.

$M/L\ Dev$: The deviation of the CoM from CBoS in the sideways direction.

H: The horizontal distance between the CBoS and the edge of the BoS.

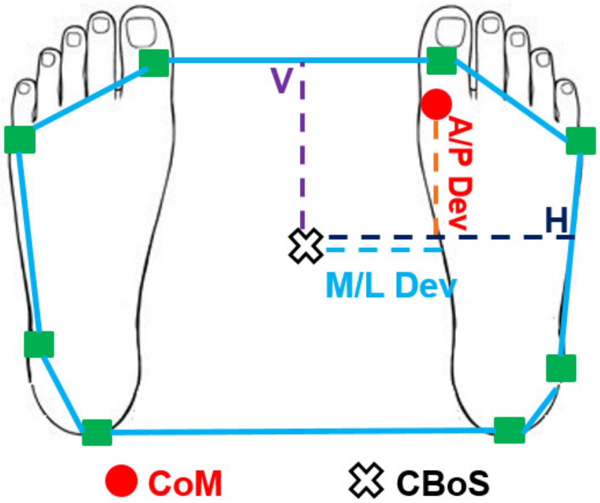


Figure 5. Proposed stability measures.

Experimental Work: Effect of Load Lifting on Postural Stability

Participants

Eight male participants were recruited from University of Miami. They were well educated and informed about the purpose of the study and the activity they would perform during the experiment. All participants were male subjects, since most of the workers in the industrial and construction sites who perform lifting tasks are males. All participants were in good health conditions, and they neither had self-reported injuries, nor musculoskeletal disorders within the previous 12 months. The experiment was approved by the University of Miami's Institutional Review Board (IRB), and each participant completed an informed consent before conducting the experiments. Table 3 shows the demographics information.

Table 3. Demographics Information of the participants in the lifting experiment.

Sample Size	Age (years)	Height (cm)	Body Mass (Kg)
8	27.13 ± 3.98	172.92 ± 6.46	83.2 ± 8.78

Equipment and Tools

A plywood shelf was constructed with an adjustable height. The shelf height could be changed from 30” to 50”. Moreover, three different boxes were used each with different weights. The laboratory incorporates a Vicon Nexus® Motion Capturing System (Oxford Metrics, United Kingdom). The motion capturing system integrates and synchronizes four Kistler force plates (Model: 9253B, sampling rate: 2400 Hz), and eight MX cameras. The reconstructed data output of the motion capturing session is shown in Figure 6, which depicts the stick figure of the subject’s lower extremity, the reflective markers as recorded by the cameras, the segments’ center lines and reference frames, and the ground reaction vectors acting on the subject. As shown in Figure 7, the data collected from the motion capturing (Mocap) system is first reconstructed and each marker is labelled in order to identify the different body segments and joints. Then the segments’ center lines are determined accordingly at the same time the synchronized force plates’ data is recorded.

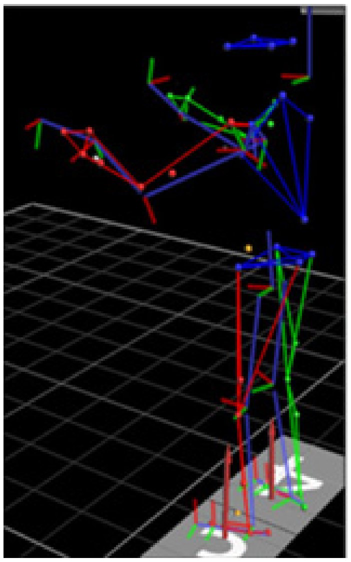


Figure 6. Stick figure and ground reaction vectors with labeled markers and reconstructed segment’s center lines.

Moreover, a special VBA code was written to calculate the proposed stability measures. The code calculates other stability measures, such as excursion of CoM in each direction, the displacement velocity in each direction, average sway length, and the mean displacement velocity. Furthermore, the code provides several charts that illustrate the deviation of CoM from the center of BoS. A brief explanation of the code will be found in the appendix.

Independent Variables

Two factors were selected as the independent variables in the study, and each one consisted of multiple levels. First, the height of the shelf, which had two levels 30” and 50”. The first level will show the effect of squatting while carrying load on stability measures. The subject was instructed not to stoop while placing the load, because squatting will provide more stability than stooping. The second level will show the effect of standing erectly while lifting a weight on stability measures. It was expected that squatting produce less stability than standing normally. The second factor was the mass of the load that would be carried and placed on the shelf. It had three levels 25lb., 35lb., and 45lb. These weights were selected based on an experiment that was conducted to study the muscle activity of accurate placing of avionics boxes (Stambolian, Eltoukhy, Asfour, & Bonin, 2011). It was expected that lifting heavy weight will generate more sway.

Dependent Variables

Vicon Nexus Motion Capturing System with its 10 cameras were used to find the trajectories of CoM. Nine stability measures were the dependent variables in this study.

The first three measures were the proposed ones. Namely, the average deviation of CoM from the CBoS in the A/P, M/L separately, and the resultant deviation in both direction together. The other six measures were excursion of CoM, the displacement velocity in each direction, average sway length, and the mean displacement velocity. These measures were selected because they are the most common measures that are used in stability studies. These measures have been widely used in occupational safety research. Later on, the proposed measures will be compared with the existing measures to check its reliability.

Experimental Protocol

In the beginning, each subject performed two practice lifts for training purpose. Then, 39 reflective markers were attached to subject's body in order to capture and record the data through the 10 cameras, as shown in Figure 7. Participants were randomly assigned to each condition of the experiment. For the 50" height, the subject carried the load and stood on front of the shelf, and the data collection started. For the 30" height, the subject carried the load and stood on front of the shelf and then he squatted. Then the data collection started. Later, the subject started to place the load on the shelf. After placing the box and before deforming the BoS, the data collection was stopped. Although two trials were enough to obtain reliable measures of postural stability, and at least two measurements are required to investigate its reliability (de Vet, Terwee, Knol, & Bouter, 2006), each subject performed three trials for each condition of the experiment, in order to increase the accuracy in the reliability calculation.

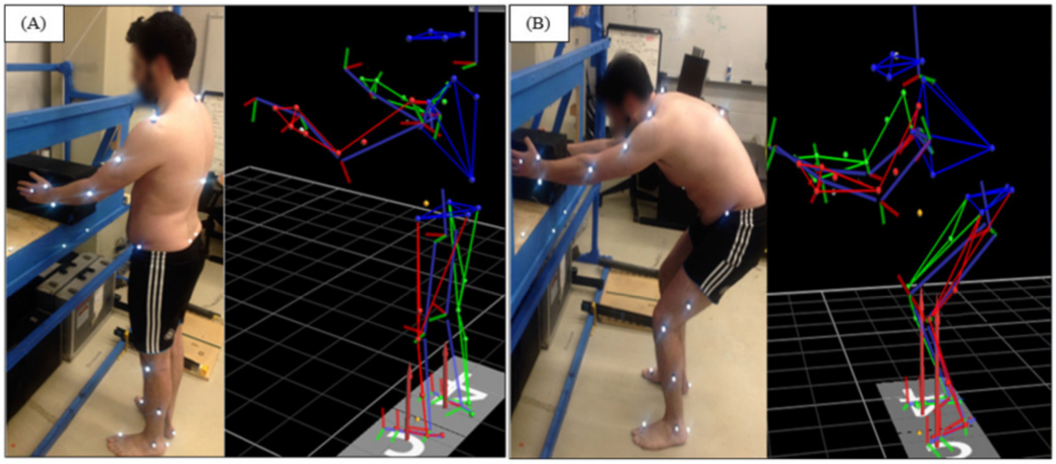


Figure 7. The 39 reflective markers that were attached to each subject. The markers were captured and recorded through motion capturing system to generate the stick figure. (A) Shows the trial of placing the box on 50" shelf height. (B) Shows the trial of placing the box on the 30" shelf height.

Statistical Analysis

The study used a full factorial design with two independent variables. Namely, shelf height, and load weight. The levels will be described in the independent variables section. The height of the shelf, and the weight of the load were selected based on a previous experiment that simulated precision placement of an avionics box on shelves (Stambolian et al., 2011). Each participant received the same six weight/ height treatment conditions. Additionally, the intraclass correlation coefficients (ICC) for each measure in each condition were calculated to investigate its reliability using SPSS. The ICC formula is shown below.

$$ICC = \frac{MS_{between} - MS_{within}}{MS_{between} + MS_{within}(n-1)}$$

Where,

ICC: Intraclass correlation coefficient

$MS_{between}$: Between-group mean square

MS_{within}: Within-group mean square

n: Number of subject in each group

Gait Stability Measures

In this study, in order to quantify walking stability during load carrying, the deviation of the extrapolated center of mass (XCoM) from the CBoS was calculated. The XCoM has been previously introduced by (A. Hof et al., 2005), and adds the linear function of the velocity of the CoM to its position (A. L. Hof, van Bockel, Schoppen, & Postema, 2007; Iqbal & Pai, 2000):

$$XCoM = CoM + \frac{V_{CoM}}{\sqrt{\frac{g}{l}}}$$

where, V_{CoM} is the velocity of the CoM (m/s), g is acceleration of gravity, and l is leg length (m). The choice of using XCoS in place of the CoM is motivated by the fact that the direction of the velocity of a system plays a fundamental role in stability: even when the CoM falls within the BoS, a system may be unstable if the velocity is directed outward the CBoS; diametrically, stability can be achieved even if the CoM is outside the BoS, as long as the velocity is directed towards the CBoS (Singh & Koh, 2009).

In equation (1) the CoM refers to the system composed of the subject together with the load carried. Its expression is provided by the following relation:

$$CoM_{system} = \frac{\sum_{i=1}^{n} Weight_{Load} \times Load's\ CoM + Weight_{Body} \times Body's\ CoM}{\sum_{i=1}^{n} Weigh_{Load} + Weight_{Body}}$$

Where *n* is the number of loads being carried (i.e. *n* = 1 with the lateral, frontal, bilateral, and *n* = 2 with the bilateral carriage). The CoM of the subject's body is directly provided by the standard Vicon's Plug-In Gait model (Zatsiorsky et al., 1990), while the CoM of the load was obtained by attaching two markers on the box (for frontal, lateral and bilateral carrying) or on the backpack (for posterior carrying).

Each gait cycle consists of two double support (DS) phases (i.e. standing on both limbs), and two single support (SS) phases (i.e. standing on a single limb). Therefore, the proposed measures quantify walking stability in DS, and SS separately by finding the maximum deviation of the XCoM from the CBoS in the anterior-posterior (A/P) and medial-lateral (M/L) directions:

$$Gait\ Stability\ in\ DS\ phase = max_i(|XCoM - CBoS|) \quad i = 1, 2,$$

$$Gait\ Stability\ in\ SS\ phase = max_i(|XCoM - CBoS|) \quad i = 1, 2.$$

Moreover, gait stability in the A/P and M/L directions were measured as the normalized distance of the deviation of the XCoM with respect to the vertical and horizontal distance between the CBoS and the edge of the BoS, respectively, as shown in Figure 8. Normalized gait stability measures were only used during the DS phase, since in the SS pahse the XCoM was located outside the BoS.

$$Gait\ Stability\ (A/P) = \frac{A/P\ Dev}{V} \times 100\%$$

$$Gait\ Stability\ (M/L) = \frac{M/L\ Dev}{H} \times 100\%$$

Where,

$A/P\ Dev$: The deviation of the XCoM from CBoS in the fore-aft direction.

V: The vertical distance between the CBoS and the edge of the BoS.

$M/L\ Dev$: The deviation of the XCoM from CBoS in the sideways direction.

H: The horizontal distance between the CBoS and the edge of the BoS.

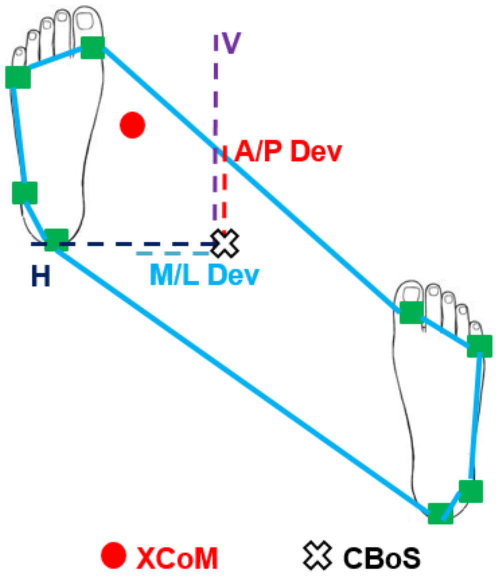


Figure 8. The normalized distance between the XCoM with respect to the distance between the CBoS and the edge of the BoS.

Experimental Work: Effect of Load Carrying on Gait Stability

Participants

Thirty volunteers (20 males, and 10 females) participated in the study. Their demographic information is shown in Table 4. The protocol of the experiment was approved by the University of Miami's Institutional Review Board (IRB). All subjects underwent a through physical examination, a health history check-up, and provided written informed consent before conducting the experiment. Subjects had fallen within the past 6 months, with history of dizziness, tremor, alcoholism, neurological disorders, diabetic symptoms, vestibular disorders, or back pain or injuries were excluded from the study.

Table 4. Demographics Information of the participants in the carrying experiment.

	Male	Female
Height	176.18±6.16	166.7±5.64
Body Mass	77.33±13.42	60.39±5.58
Age	27.3±2.64	21.8±2.5
Sample Size	20	10

Equipment and Tools

The experiments were all conducted at the Biomechanics laboratory at the University of Miami with the Vicon Motion Capturing System (Oxford Metrics, United Kingdom) Nexus software version1.6.1.57351 and 12 MX cameras with a resolution of 1024 x 1024 pixel, and sampling rate 120 Hz. with the force plates were used. Kinematic data were captured and recorded. Moreover, to simulate the lateral carrying 2 empty toolboxes were used, and it carried different weights. The dimensions of the toolbox is 15”× 6” × 6”, as shown in Figure 8 (a). The same toolbox could be carried with 2 hands in front of the body to mimic anterior carriage. In addition, a standard backpack was used for the posterior carriage, as show in Figure 8 (b). Moreover, 4 five-pound weights were used and they were either placed inside the toolboxes or inserted in the backpack. The weights are shown in Figure 8 (c). When the toolboxes were used, the weights were placed on the bottom and exactly in the middle to avoid wrist twisting. Furthermore, foam panels were place around the weight to assure that the weights would not move inside the toolbox during walking.

Figure 9. Different tools used to simulate various carrying methods. (A) A toolbox was used to simulate lateral, and anterior carrying. (B) A backpack was used to simulate posterior carriage at shoulder level. (C) The weights used in the experiment.

Moreover, a special VBA code was written to calculate the deviation of the XCoM from the CBoS in the A/P and M/L directions. Furthermore, the code provides several charts that illustrate the CoM, XCoM paths, and the MDS. A brief description of the code can be seen in the Appendix.

Additionally, spine biomechanical model was used in order to find the compression, shear forces, and moments of the L5/S1 vertebra. The model was developed by (Eltoukhy et al., 2016).The spine was composed of three-dimensional linked segments representative of the five lumbar vertebrae and the thoracic vertebrae T12, T11, and T10.

All vertebrae were treated as rigid bodies, and modeled as a chain connected to each other via the intervertebral discs. The movement of the spine was driven by the relative motion between the pelvis and thorax, which was computed via a motion capture system. The location of the pelvis was computed by tracking four stereotactic markers applied on both anterior (left anterior superior iliac spine, and right anterior superior iliac spine) and posterior (left posterior superior iliac spine, and right posterior superior iliac spine) aspects of the ilium. The pelvic coordinate frame was centered in the midpoint between the two anterior superior iliac spine markers (gray point). The principal directions were axial (red arrow), medial-lateral (green arrow), and anterior-posterior (blue arrow), as shown in figure 9.

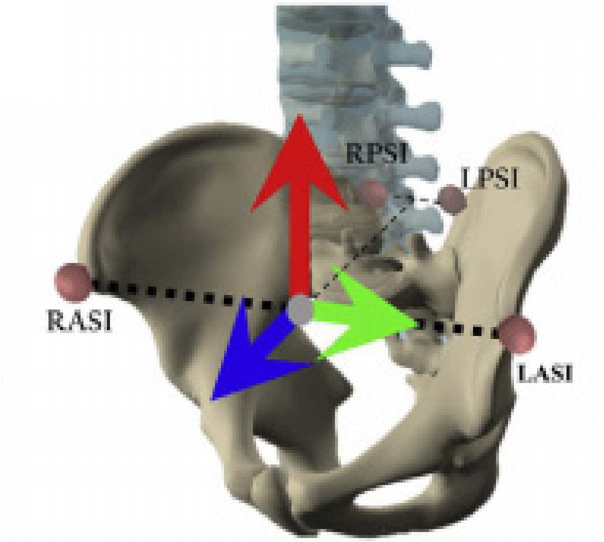


Figure 10. Pelvic location and movement directions.

The thorax was discriminated by four other markers located at the midpoint of the two clavicles (CLAV), on the sternum above the solar plexus (STRN), on the superior spinal process of the thoracic vertebra T10, and on the superior spinal process of the cervical vertebra C7. The origin of its reference frame was at the CLAV. The axes of the reference frame were: axial (red arrow), medial-lateral (green arrow), and anterior-posterior (blue arrow), as shown in figure 10.

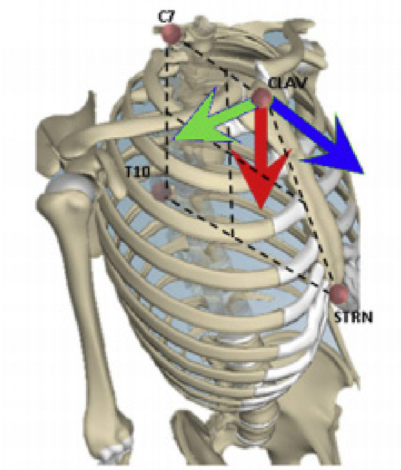


Figure 11. Thorax location and movement directions.

The local coordinate frame of each vertebra had its center in the center of mass of that vertebra; the axial direction laid on the sagittal plane, and was tangential to the spine curvature; the anterior-posterior direction also lay in the sagittal plane, but was orthogonal to the tangent of the spine curvature; and, the medial-lateral direction was orthogonal to the axial and anterior-posterior directions, as shown in figure 11.

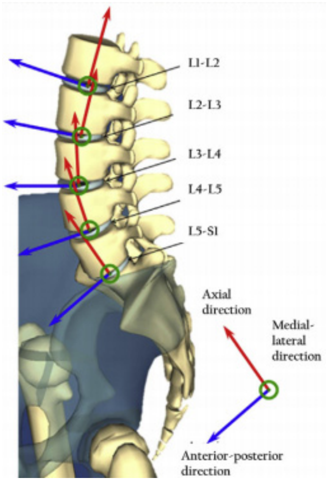


Figure 12. Vertebra movement directions.

For the lumbar spine, the motion of a vertebra was defined relative to the vertebra below it. It started with the L5 relative to a fixed sacrum (S1), and moved up the spine to L1. The function of each intervertebral disc was to allow 6 degrees of freedom of movement between the vertebrae and to transmit the load from one rigid body to the other.

Independent Variables

Two factors were the independent variables. Namely, load weight and carrying methods. Each factor had multiple levels. Load weight consisted of 10 lbs and 30 lbs. Carrying methods consisted of frontal, lateral, bilateral, and posterior carriages, as shown in Figure 12. For anterior carriage, subjects were instructed to carry the load at about waist level without supporting it against the body, and at self-chosen horizontal distance from the torso. In general, the elbows were flexed slightly more than 90°. In lateral carriage, participants carried the load with their dominant hand. For bilateral carriage, the loads were split in half between each box.

Figure 13. Carrying methods investigated: (A) Frontal, (B) Lateral, (C) Bilateral, and (D) Posterior. Note that a hole was made in the backpack to allow the motion capturing system to capture the T10 reflective marker.

Dependent Variables

Vicon Nexus Motion Capturing System with its 12 cameras were used to find the trajectories of the CoM. Later, a custom VBA code was used to find the trajectories of the XCoM, and its deviation from the CBoS in A/P and M/L direction during DS and SS phase. Additionally, Vicon® Motion Capturing System was used to measure the spatio-temporal gait parameters. Namely, double support duration, expressed as percentage of gait cycle, stride length, measured in meters, walking speed expressed in meters per second (m/s), cadence, expressed in steps per minute (steps/min), and step width measured in (mm). Moreover, lumbar spine kinematics were measured in terms of extension/ flexion and lateral bending in (º), as shown in Figure 13. Finally, the compression, shear forces, and moments generated at the L5/S1 vertebra were calculated.

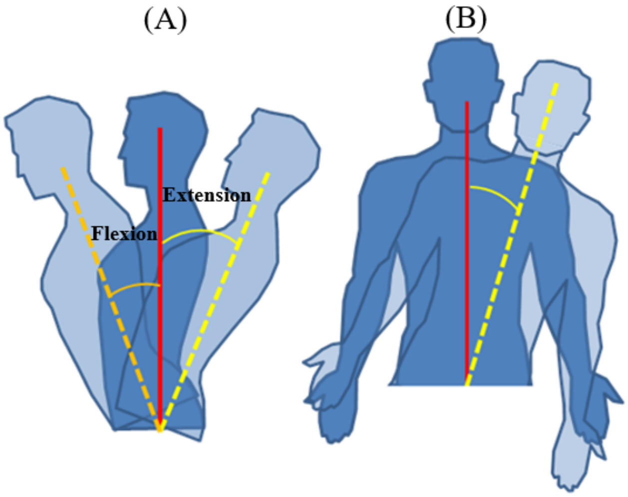


Figure 14. (A) Trunk flexion/ extension; (B) Trunk lateral bending.

Experimental Protocol

After placing the reflective markers, each participant walked without carrying loads in the designated area with self-selected speed. These trials served as a baseline, which will be compared with each condition of the experiment. Later, subjects were handed the load, instructed to look forward, and walked in a straight line for the 4 m walkway. Each condition was repeated 3 times. Since each participant went through each condition, an order effect might occur. It refers to the order of the conditions having an effect on their behavior. In other words, thee performance in the second trial might be better, because of the practice effect, or worse, because of the fatigue effect. Therefore, the sequence of treatment conditions was randomized for each subject, in order to reduce the chance of variation between individuals skewing the results and also, reduces the chance of practice or fatigue effect influencing the results. The randomized order of each subject is shown in the appendix.

Statistical Analysis

The experiment consisted of two independent variables. Namely, load weight (two levels) and carrying methods (four levels). Each factor had multiple levels. Each condition was repeated 3 times. All trials were randomly selected for each participant to counterbalance the learning effect. Dependent measures consisted of gait stability measures, gait parameters, and loads on L5/S1. One-way ANOVA was used to test if there was a significant difference between the baseline (i.e. normal gait without carrying) and other conditions. Since each participant was exposed to each condition of the experiment, repeated measures ANOVA was used for each dependent variable. Moreover, Tukey's post-hoc test was used to compare between the levels of each factor if it was found significant. Subjects were included in the ANOVA table as a random factor, to account for variability within and across subjects. The level of significance used in all the statistical test was $\alpha = 0.05$. Minitab® version 17 was used analyzing the data.

CHAPTER 4: RESULTS

Effect of Load Lifting on Postural Stability

Each stability measure was calculated for each of the six weight/ height treatment conditions. Mean and standard deviation values of each parameter are shown Table 5. The statistical significance of each parameter is shown in Table 6.

Table 5. Mean and standard deviation of each stability measure for different weight/ height treatment conditions.

Height (“)			30			50		
Weight (lb.)			25	35	45	25	35	45
Proposed Measures	Average M/L Deviation (mm)	Mean	22.01	29.37	22.27	18.33	20.14	23.19
		S.D.	5.23	8.93	3.37	3.81	3.13	4.08
	Average A/P Deviation (mm)	Mean	90.81	101.02	104.76	44.10	39.6	59.46
		S.D.	10.24	6.09	6.33	6.15	8.35	9.62
	Total Deviation (mm)	Mean	94.74	120.09	110.22	44.42	50.57	95.0
		S.D.	10.235	22.103	12.22	10.51	11.5	15.14
Existing Measures	M/L Excursion (mm)	Mean	43.67	98.47	90.07	50.06	43.65	51.72
		S.D.	7.73	11.83	8.96	12.12	8.79	5.62
	A/P Excursion (mm)	Mean	177.4	181.95	120	100.14	107.63	111.68
		S.D.	25.28	6.32	6.85	7.31	6.88	10.8
	M/L Velocity (mm/sec)	Mean	2.91	3.54	4.67	2.01	3.57	3.85
		S.D.	1.64	0.79	1.57	2.83	0.67	0.79
	A/P Velocity (mm/sec)	Mean	11.05	11.23	10.99	9.85	7.82	8.94
		S.D.	5.35	2.8	1.54	1.75	1.65	1.22
	Mean Displacement Velocity (mm/sec)	Mean	11.44	12.26	9.5	10.6	9.57	12.16
		S.D.	1.64	1.69	1.76	1.14	1.75	1.71
	Average Sway Length (mm)	Mean	0.74	0.84	0.78	0.64	0.59	0.81
		S.D.	0.18	0.11	0.12	0.12	0.1	0.08

Height Effect on Postural Stability

From the two-way repeated measures ANOVA for each stability measure, it was obvious that the height factor had highly significant impact on all dependent variables ($p < 0.01$), as seen in Table 6. Moreover, the shelf height of 30” produced less stability than the 50” height, because the subject was squatting in the first condition, which produces more stress on muscles than the second condition (Stambolian et al., 2011). Therefore, when the height of the working surface is lowered, body stability decreases, as shown in the Figure 14.

Weight Effect on Postural Stability

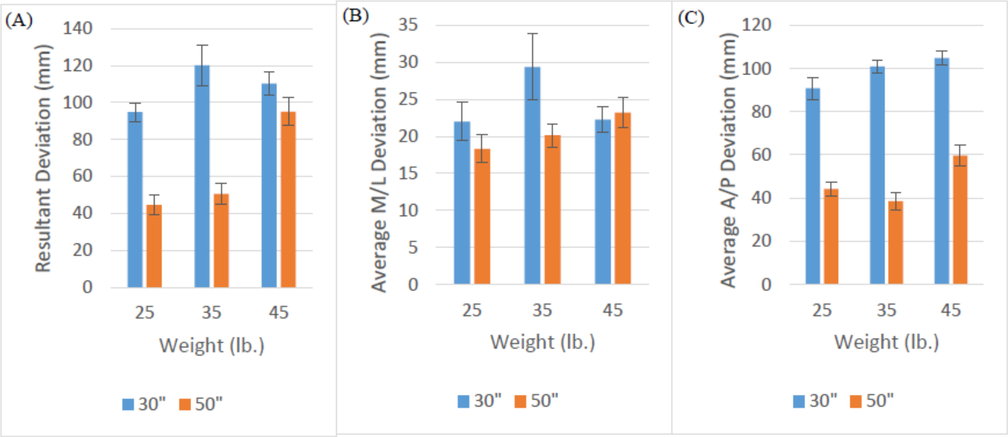
As shown in Table 4, the weight factor had a significant effect on all stability measures ($p < 0.0.05$), except the A/P velocity. According to (Bhattacharya et al., 2002),an effect on all or any stability measure implies an increase in postural sway or instability, because under ideal conditions of upright postural stability, a person would produce minimal sway, whereas poor postural stability would result in a significant increase of most sway measures, such as sway velocity, and CoM excursion (Fernie, Gryfe, Holliday, & Llewellyn, 1982; Maki et al., 1994). Therefore, the weight factor has a significant impact on body sway. Moreover, since there are three different levels in the weight variable (i.e. 25, 35, and 45 lb.), Tukey's post-hoc analysis was used to check the significant difference between the levels. The tests showed that there was a significant difference between 25 lb. and 45 lb. ($p < 0.001$). Nevertheless, there was no significant difference when the load was 35 lb. and the other weights. Therefore, when the lifted weight increases, body stability decreases, as shown in Figure 14.

Interaction of Height and Weight Factors

According to the repeated measures ANOVA, the interaction effect of height and weight factors was highly significant on all stability measures ($p< 0.01$) except the A/P velocity, as shown in Table 6. Therefore, increasing the load being carried with non-erect posture produces more instability. Based on our knowledge, none of the previous studies investigate the effect of task-related factor (i.e. manual material handling) on postural stability.

Table 6. Summary of statistical results (p-value) for the effect of load placing at different heights on several measures of stability. (-) $p \geq 0.05$; (+) $0.05 > p \geq 0.01$; (++) $0.01 > p \geq 0.001$; (+++) $p < 0.001$.

	Stability Measure	**Weight (W)**	**Height (H)**	**W X A**
Proposed Measures	**Average M/L Deviation**	++	+++	+++
	Average A/P Deviation	++	+++	+++
	Total Deviation	+++	+++	+++
Existing Measures	**M/L Excursion**	+++	+++	++
	A/P Excursion	+++	+++	+++
	M/L Velocity	+++	++	+
	A/P Velocity	-	+++	-
	Mean Displacement Velocity	+	++	+++
	Average Sway Length	+++	+++	+++



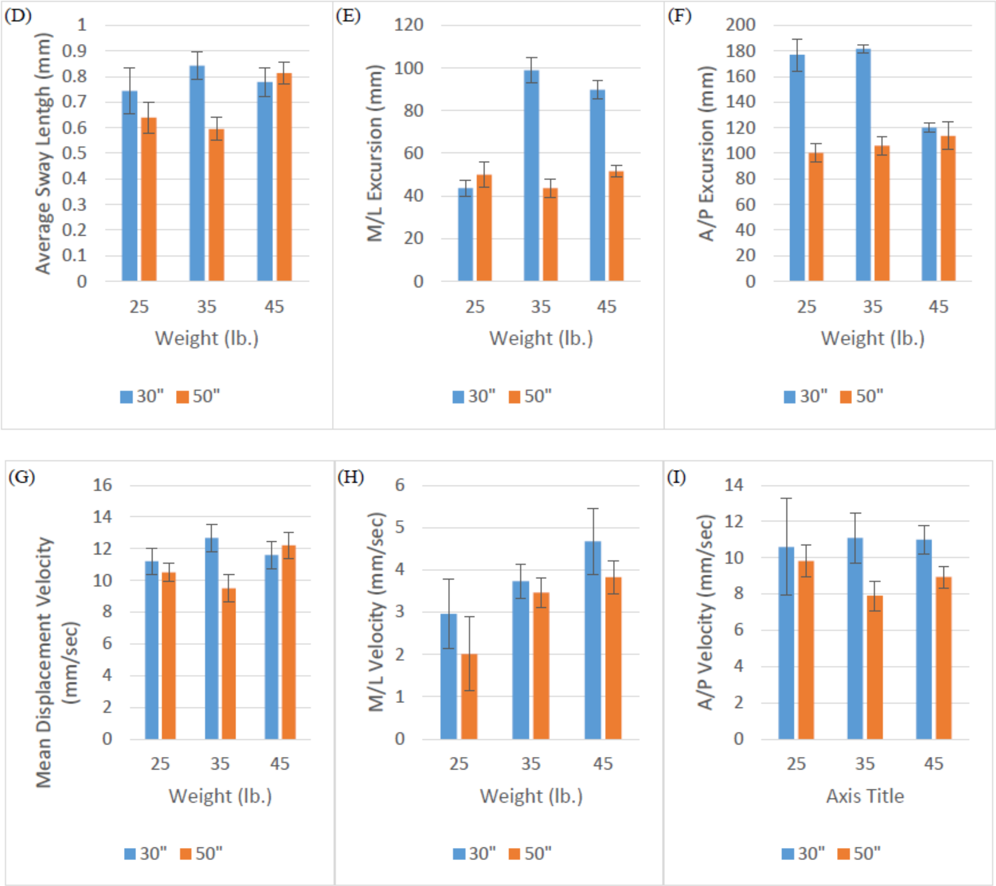


Figure 15. Means with 2 standard error range of the proposed measures: (A) Resultant deviation, (B) M/L deviation, (C) A/P deviation, and the existing measures (D) average sway length, (E) M/L excursion, (E) A/P excursion, (G) mean displacement velocity, (H) M/L velocity, (I) A/P velocity . Obviously, lowering the working surfaces, decreased body stability. Additionally, heavy loads increased instability.

The Effects of Different Weights Lifting with Different Heights on Normalized Postural Stability Measures

The two-way repeated measured ANOVA revealed that the height factor had significant impact on Normalized Postural Stability Measures in the A/P and M/L directions ($p < 0.01$). Moreover, 30” shelf height produced less stability than the 60” height, because the subjects changed their body posture from the upright condition to squatting. Therefore, when the height of the working surface is lowered, body stability decreases.

The weight being carried significantly affected the Normalized Postural Stability Measures in both direction ($p < 0.05$). Tukey's post-hoc test showed that there was a significant difference between 25 lb. and 45 lb. ($p < 0.001$). Nevertheless, there was no significant difference when the load was 35 lb. and the other weights. Therefore, when the lifted weight increases, body stability decreases. Additionally, the interactive effect of the weight and shelf height had a significant effect ($p< 0.01$). Therefore, increasing the load being carried with non-erect posture generated more instability, as shown in Figure 16(a – b).

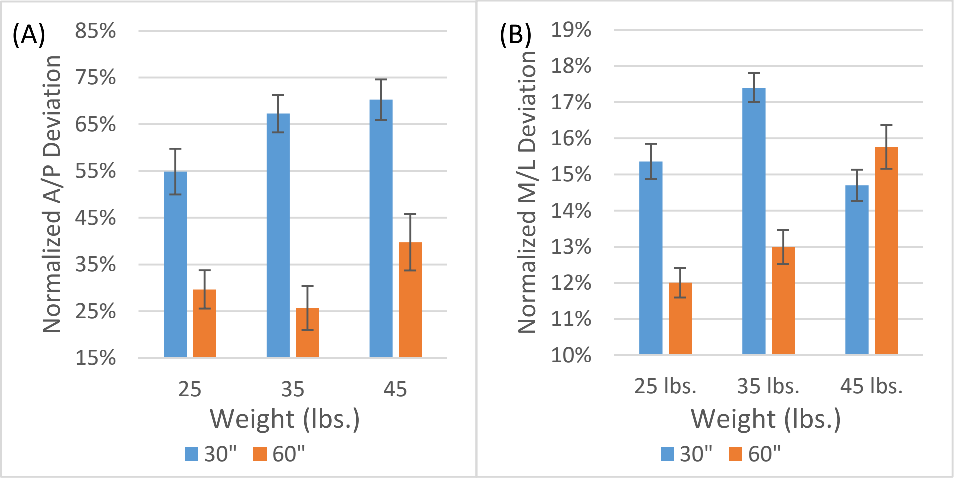


Figure 16. Means with 2 standard error range of the Normalized deviation of the CoM with respect to the Distance between CBoS and Edge of the BoS in the (A) A/P, and (B) M/L directions.

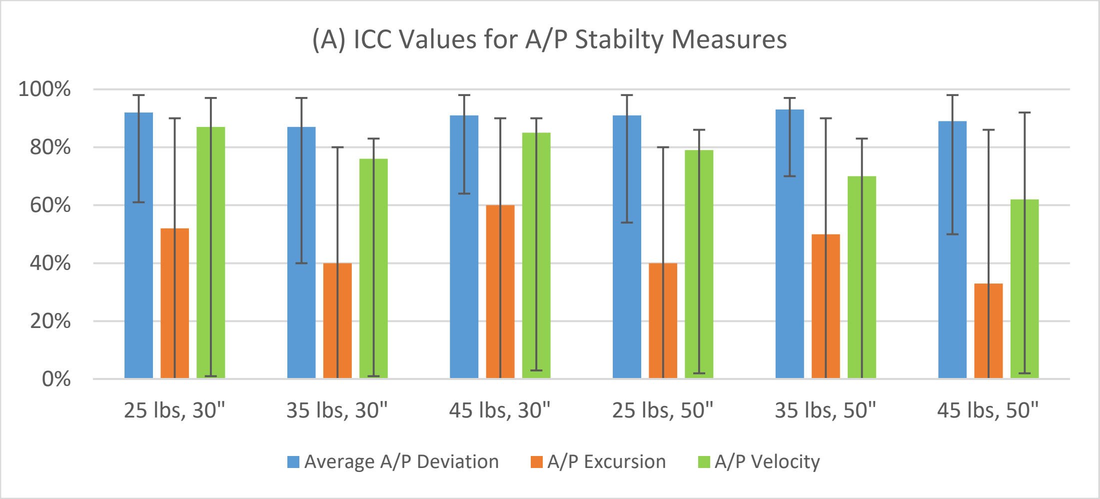
Reliability of the Proposed Stability Measures

Measurements are almost always exposed to various types of errors, which cause the measured value to differ in each trial of an experiment. If reliability is high, measurement errors are small in comparison to the true differences between subjects. The parameter that is used to assess reliability is called intraclass correlation coefficient (ICC). It takes the values between zero and one, with a value close to one corresponding to small amount of variability, and a value close to zero corresponding to large amount of variability due to error. According to (Bartlett & Frost, 2008), in comparing between different measures, using the one with higher reliability (i.e. higher ICC) will give greater statistical power to find differences between groups. Reliability is a useful tool to compare different measurements methods. Reliability refers to the extent by which the measurement is inherently reproducible, or the degree to which the measurement influenced by measurement errors (Bruton, Conway, & Holgate, 2000; Pinsault & Vuillerme, 2009). An advantages of using reliability of measures is that it can be used to compare them even if they were given in different scales, as the ICC is dimensionless (Bartlett & Frost, 2008).

Therefore, the reliability of the proposed measures will be compared to other stability measurements in order to check its reliability and accuracy of capturing stability. In order to compare the reliability of each stability measure, ICC values were calculated between the three replications of each weight/ height treatment condition. As described earlier that the resultant deviation measures stability in both directions (i.e. A/P, and M/L) together, its ICC should be compared with the measures that evaluate stability in both directions, such as mean displacement velocity, and average sway length. Among all the three measures, the most reliable one was the resultant deviation which had the highest ICC, as shown in Table 7 and Figure 15 (a). Moreover, the average A/P deviation should be compared with the A/P excursion, and A/P velocity. Again the proposed measure showed more reliability than the other, as shown in Figure 15 (b). Same conclusion was drawn with the average M/L deviation when it was compared with M/L excursion, and M/L velocity, as shown in Figure 15 (c). Another indication of reliability of the proposed measures can observed from the narrow 95% confidence interval of its ICC value, as shown in Table 7.

Table 7. Intraclass correlation coefficient (ICC) values with its 95% CI for each stability measure. Where the lower bound of the CI was negative, it was truncated to 0, since ICC value can be from 0 to 1.

Height (cm)			**30**			**50**		
Weight (N)			**25**	**35**	**45**	**25**	**35**	**45**
Proposed Measures	**Average A/P Deviation**	ICC	0.92	0.87	0.91	0.91	0.93	0.89
		95% CI	0.61-0.98	0.4-0.97	0.64-0.98	0.54-0.98	0.7-0.97	0.5-0.98
	Average M/L Deviation	ICC	0.79	0.83	0.89	0.80	0.81	0.85
		95% CI	0.4-0.95	0.4-0.96	0.5-0.97	0.3-0.96	0.4-0.96	0.42-0.97
	Total Deviation	ICC	0.96	0.93	0.91	0.93	0.93	0.94
		95% CI	0.8-0.98	0.63-0.97	0.51-0.98	0.7-0.96	0.63-0.97	0.7-0.99
Other Measures	**M/L Excursion**	ICC	0.46	0.32	0.20	0.55	0.50	0.40
		95% CI	0.1-0.77	0-0.69	0-0.71	0-0.73	0-0.71	0-0.79
	A/P Excursion	ICC	0.52	0.40	0.60	0.40	0.50	0.33
		95% CI	0-0.9	0-0.8	0-0.9	0-0.8	0-0.9	0-0.86
	M/L Velocity	ICC	0.63	0.67	0.74	0.71	0.69	0.68
		95% CI	0-0.9	0-0.81	0-0.77	0-0.75	0-0.82	0-0.84
	A/P Velocity	ICC	0.87	0.76	0.85	0.79	0.70	0.62
		95% CI	0.01-0.97	0.01-0.83	0.03-0.9	0.02-0.86	0-0.83	0.02-0.92
	Mean Displacement Velocity	ICC	0.82	0.85	0.88	0.81	0.81	0.84
		95% CI	0.35-0.9	0.2-0.9	0.5-0.9	0.25-0.95	0.16-0.96	0.14-0.97
	Average Sway Length	ICC	0.78	0.74	0.70	0.80	0.70	0.75
		95% CI	0.1-0.97	0.3-0.95	0.24-0.93	0.3-0.97	0.29-0.93	0.32-0.95



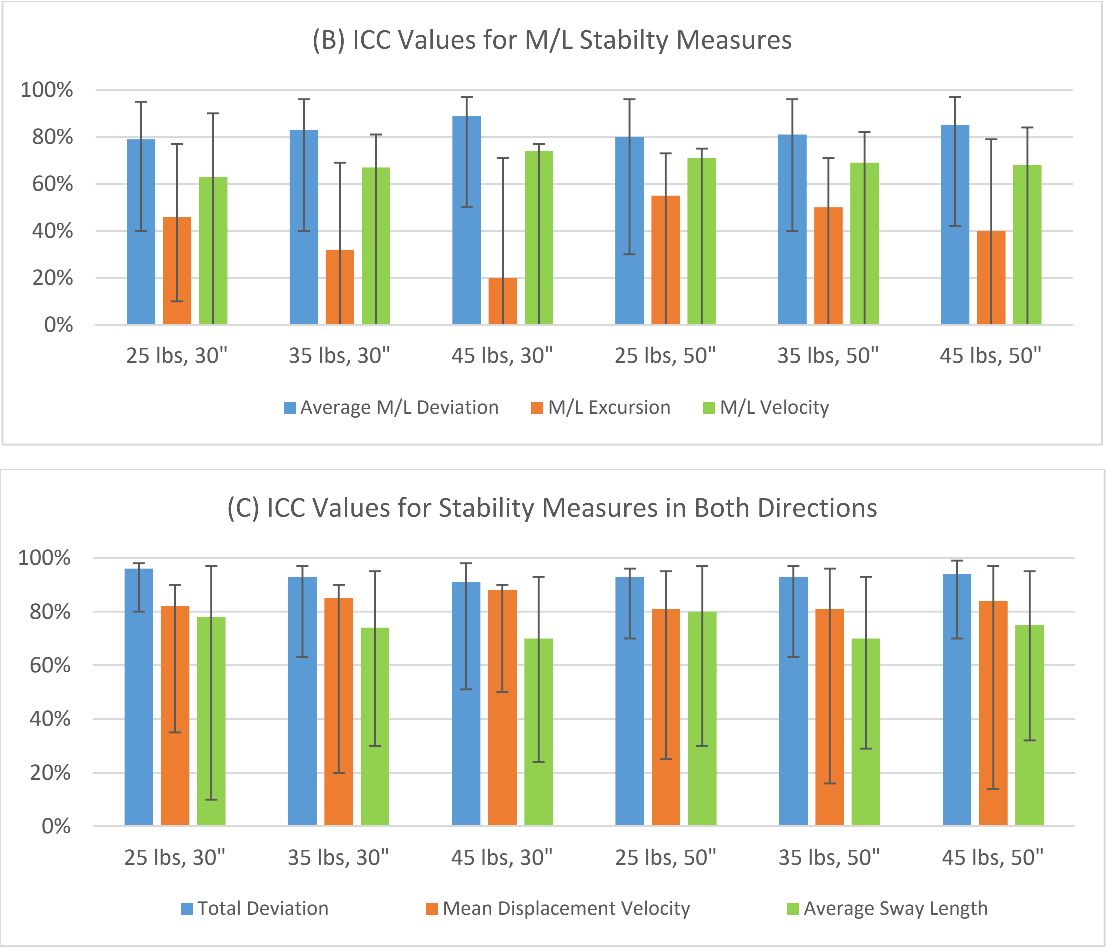


Figure 17. Comparison between proposed stability measures (blue bars) and existing measures (orange and green bars) in terms of ICC values with 95% CI. (A) A/P stability measures, (B) M/L stability measures, (C) Stability measures in both directions.

Effect of Load Carrying on Gait Stability

Deviation of the XCoM from the CBoS in the A/P direction During DS phase

The repeated measure ANOVA revealed the significant effects of the weight, carrying methods and their interaction on peak A/P deviation of the XCoM during DS phase ($p < 0.05$). Tukey's post-hoc analysis showed that heavier weights generated higher deviation of the XCoM from the CBoS. Moreover, frontal carriage produced higher instability compared to the others. Additionally, bilateral method resulted in significantly shorter deviation compared to the others. In each carrying method there were no significant differences between the 10 lbs, and 30 lbs. except in the lateral carriage. While carrying 10 lbs. bilateral, lateral, and posterior methods were significantly lower than frontal method. However, in the 30 lbs. frontal, lateral, and posterior methods were significantly higher than the bilateral method. All the conditions were significantly different compared to the baseline ($p < 0.001$), except the bilateral carriage of 10 lbs. ($p = 0.145$), as shown in Figure 16(a).

Deviation of the XCoM from the CBoS in the A/P direction During SS phase

The effects of the load, and carrying methods were statistically significant on the peak A/P deviation of the XCoM during SS phase ($p < 0.05$). Tukey's analysis indicated that heavier weight produced larger deviation during SS phase compared to lighter weights. Moreover, frontal carriage generated significantly higher deviation than all the others. Additionally, bilateral method was significantly smaller than all the others. There was no significant difference between lateral and posterior methods. Additionally, all the conditions were significantly higher than the baseline ($p < 0.05$), except for the bilateral carriage of 10 ($p = 0.63$), and 30 lbs. ($p = 0.32$), as shown in Figure 16(b).

Deviation of the XCoM from the CBoS in the M/L direction During DS phase

The weight, carrying methods and their interaction significantly influenced peak M/L deviation of the XCoM during DS phase ($p < 0.001$). Heavier weight resulted in higher deviation. Moreover, lateral carriage generated the largest deviation among the others. Additionally, in each carrying method there was no significant difference between the 10 lbs. and 30 lbs. except in lateral condition, where carrying 30 lbs. laterally was significantly larger than carrying 10 lbs. Moreover, lateral carriage of 10 lbs. was significantly higher than both posterior and bilateral carrying of the same weight. However, no significant difference was observed while carrying 30 lbs. frontally, posteriorly, or bilaterally. Both frontal and lateral carriage of 10 and 30 lbs. were significantly different from the baseline, as shown in Figure 16(c).

Deviation of the XCoM from the CBoS in the M/L direction During SS phase

Peak M/L deviation of the XCoM during SS phase was significantly affected by the weight, carrying method and their interaction ($p < 0.001$). Heavier weight resulted in less walking stability compared to the others. Lateral carriage of 30 lbs. was significantly higher than all other conditions. Additionally, in each carrying method there was no significant difference between the 10 lbs. and 30 lbs. except in lateral condition, where carrying 30 lbs. laterally was significantly larger than carrying 10 lbs. Moreover, lateral carriage of 10 lbs. was significantly higher than both posterior and bilateral carrying of 10 lbs. Moreover, lateral carriage of 10 lbs. was significantly higher than bilateral carriage of 10 lbs. only, but insignificantly different compared to other methods. All the conditions were significantly different ($p < 0.01$) compared to the baseline except for the bilateral carriage of 10 ($p = 0.771$), and 30 lbs. ($p = 0.438$), as shown in Figure 16(d).

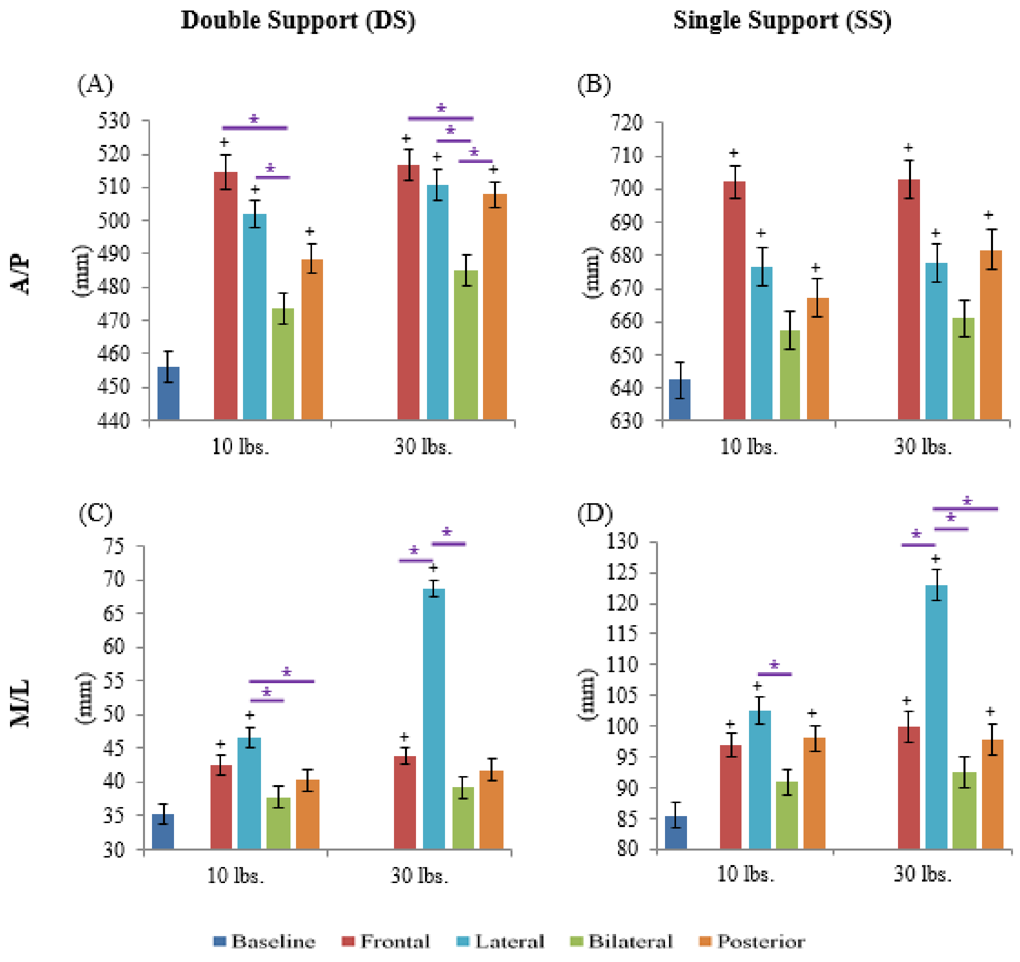


Figure 18. (A) Peak A/P deviation of the XCoM during DS (B) SS phases (C) Peak M/L deviation of the XCoM during DS (B) SS phases. Data are reported in terms of mean and 2 standard deviations. (+) indicates significant difference compared to the baseline. (*) indicates significant difference.

Normalized deviation of the XCoM with respect to the Anterior Distance between CBoS and Edge of the BoS

The repeated measure ANOVA showed the significant effects of the weight, carrying methods and their interaction ($p < 0.05$). Tukey's post-hoc analysis indicated that heavier weights generated normalized deviation. Moreover, frontal carriage produced higher instability compared to the others. Additionally, bilateral method resulted in significantly shorter normalized deviation compared to the others. All the conditions were significantly different compared to the baseline ($p < 0.001$), except the bilateral carriage of 10 lbs. (p =0.145), as shown in Figure 18 (a).

Normalized deviation of the XCoM with respect to the Lateral Distance between CBoS and Edge of the BoS

The weight, carrying methods and their interaction significantly affected the normalized M/L deviation of the XCoM ($p < 0.001$). Heavier weight resulted in higher normalized deviation. Moreover, lateral carriage was the most unstable condition among the others. No significant difference was observed while carrying 30 lbs. frontally, posteriorly, or bilaterally. Both frontal and lateral carriage of 10 and 30 lbs. were significantly different from the baseline, as shown in Figure 18 (b).

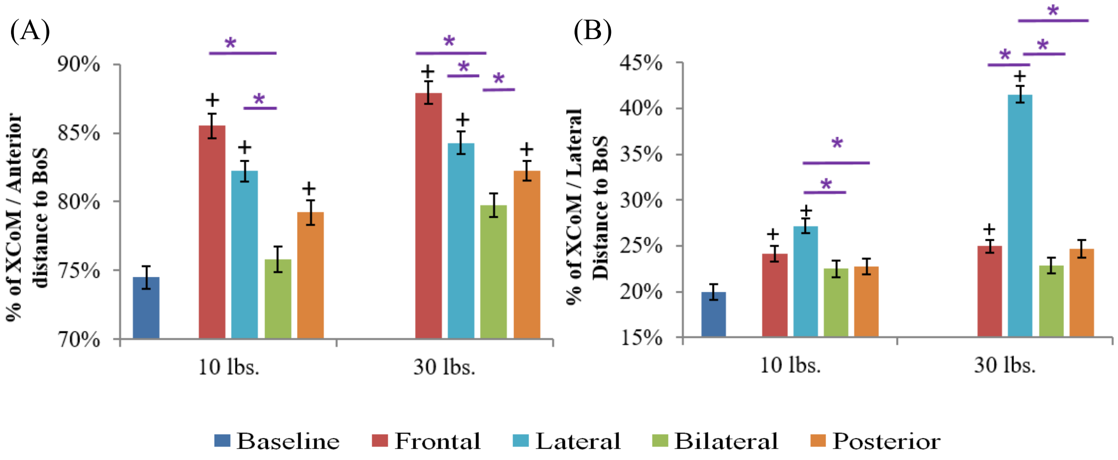


Figure 19. Normalized deviation of the XCoM with respect to the Distance between CBoS and Edge of the BoS in the (A) A/P, and (B) M/L directions. Data are reported in terms of mean and 2 standard deviations. (+) indicates significant difference compared to the baseline. (*) indicates significant difference.

Effect of Load Carrying on Gait Parameters

The weight, carrying method and their interaction caused a significant effect on cadence ($p < 0.001$). Heavier weight resulted in higher steps per minute. Furthermore, frontal carriage generated significantly higher cadence compared to the other. Frontal carriage of 30 lbs. was significantly larger than all the others. In each method, carrying 30 lbs. produced significantly larger cadence than the same method of carrying 10 lbs. except in the posterior carriage of the same weight. No significant difference was found between bilateral, lateral, and posterior carriage of 10 lbs. The same result was found while carrying 30 lbs. Only frontal carriage of 10, and 30 lbs. with lateral carriage of 30 lbs. were significantly different with respect to the baseline condition, as shown in Figure 17(a). The weight, carrying method and their interaction had a significant effect on the length of the stride while walking ($p < 0.05$). Heavier weight resulted in shorter stride length compared to the others. Frontal carriage of 30 lbs. produced significantly shorter stride length than all the others except carrying 10 lbs. frontally. In the 10 lbs. level, frontal method was significantly lower than both bilateral and posterior carriages. While carrying 30 lbs, the only significance that was found was between frontal and all other methods ($p<0.01$). The only condition that was significantly different from the baseline condition ($p < 0.01$), as shown in Figure 17(b). Only the load being carried significantly influenced the duration of DS ($p < 0.001$). Heavier weight produced longer duration of DS than lighter weight. In the 30 lbs. level, all the carrying methods were significantly higher than the baseline ($p < 0.01$) except for the bilateral condition, as shown in Figure 17(c). Step width was significantly affected by the weight, carrying method and their interaction ($p < 0.01$). In the 10 lbs. level, posterior carriage was significantly larger than the others except the frontal method. However, while carrying 30 lbs., frontal method was significantly the largest among the others. Both of them resulted in a narrower step width compared to the baseline conditions, as shown in Figure 17(d).

No significant effects of the independent variables were found on walking speed (*p* = 0.1). Moreover, none of the conditions were significantly different with respect to baseline (*p* =0.77), as shown in Figure 17(e).

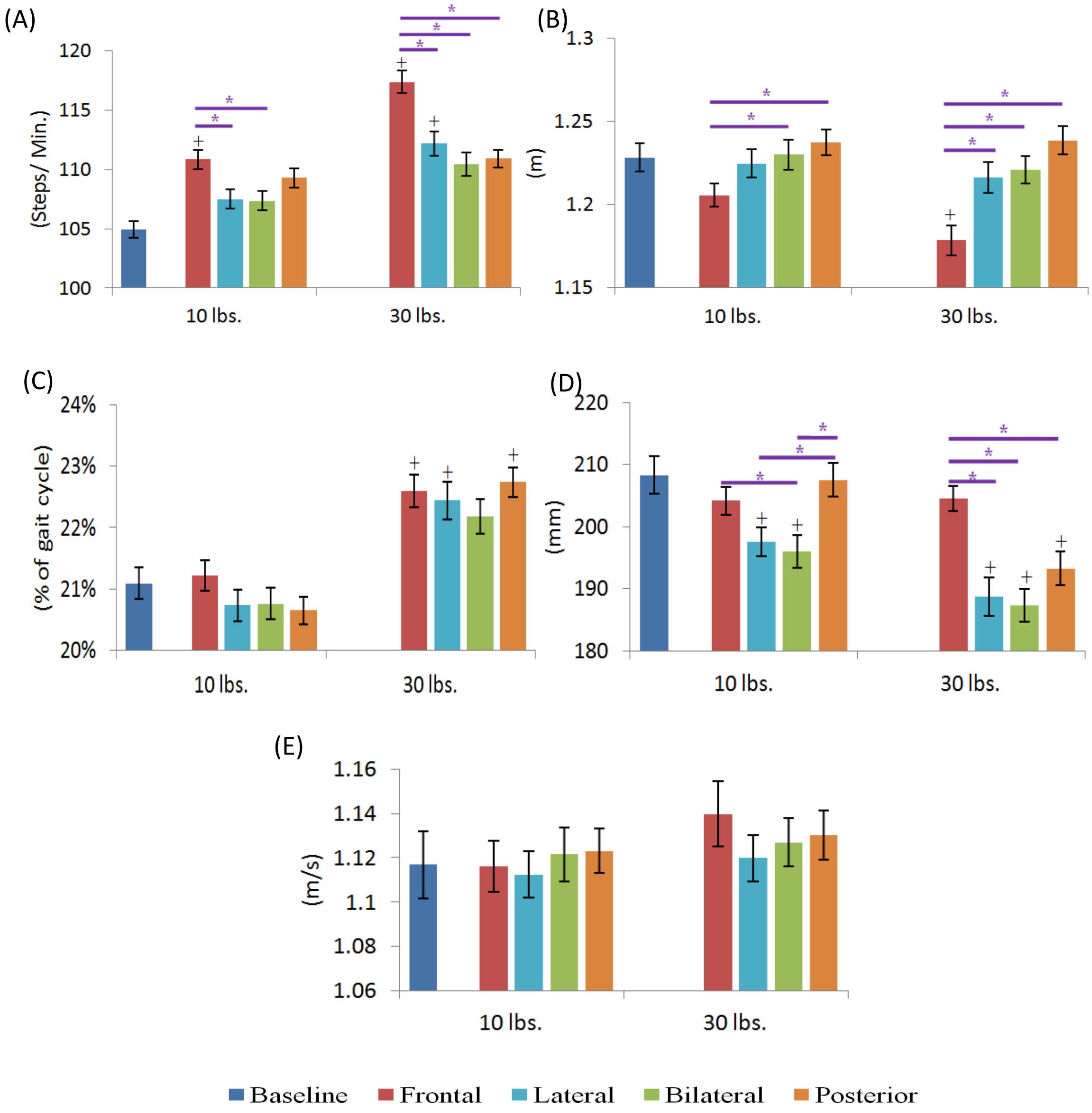


Figure 20. The effect of different load carrying with different carrying methods on gait spatio-temporal parameters. (A) Cadence. (B) Stride length. (C) Double support duration. (D) Step width. (E) Walking speed. Data reported in mean (standard deviation).

Effect of Load Carrying on Lumbar Spine Kinematics and Kinetics

Trunk Extension and Flexion

The weight, carrying methods, and their interaction significantly affected trunk flexion and extension ($p<0.001$). The heavier weights being carried, the more effect was on trunk kinematics ($p<0.01$). Posterior carriage produced the highest trunk flexion among all the others ($p<0.001$), followed by lateral carriage ($p<0.001$). Moreover, frontal carriage generated higher trunk extension compared to the others ($p<0.001$). With the addition of the weight, the effect on trunk kinematics exaggerated when participant carried the load posteriorly, and laterally. Moreover, frontal carriage of 10 lbs., and frontal, lateral and posterior carriage of 30 lbs. were significantly different from the baseline ($p<0.01$), as shown in Figure 18(a).

Carrying methods significantly affected trunk lateral bending ($p<0.001$). The weight being carried did have a significant effect ($p=0.264$). However, the interactive effect significantly influenced the lateral bending of the trunk ($p<0.001$). Both frontal and lateral carrying methods were significantly different from both posterior and bilateral method ($p<0.01$). While carrying 30 lbs. laterally, the effected on trunk lateral bending was significantly higher compared to the 10 lbs. Compared to the baseline, lateral carriage of 10 and 30 lbs. with frontal carriage of 30 lbs. were the only conditions that were significantly different, as shown in Figure 18(b).

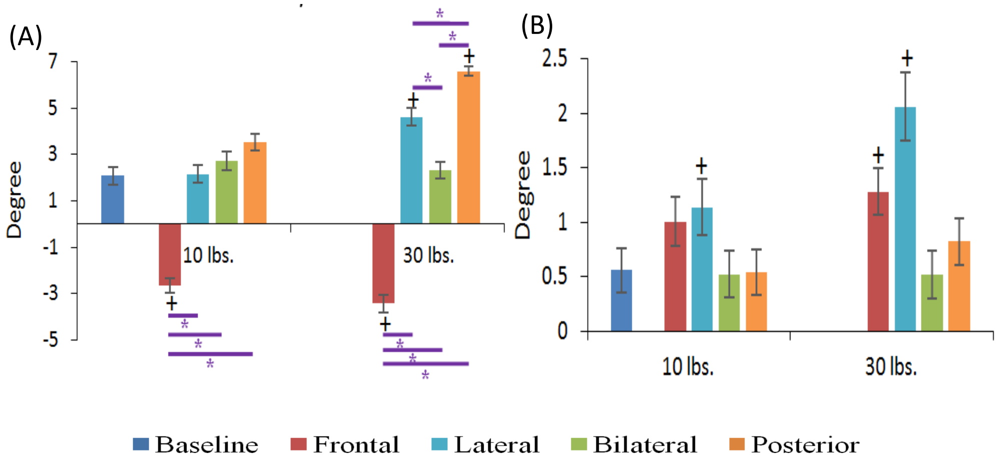


Figure 21. The effect of different load carrying with different carrying methods on lumbar spine kinematics. (A) Trunk extension/ flexion. (-ve) indicates trunk extension. (B) Trunk lateral bending. (+) indicates significant difference compared to the baseline. (*) indicates significant difference.

Normalized Compression Force

The weight and carrying methods had significant main effects on the compression force at the L5/S1 intervertebral disc ($p < 0.01$). No significant interactive effect was found. Heavier weight produced significantly larger compression force. Bilateral carrying generated significantly smaller compression than all the others. No significant difference was found between posterior, lateral, or frontal methods. The only condition that was insignificantly different from the baseline condition was the bilateral carriage of 10 lbs. ($p = 0.63$), as shown in Figure 19(a).

Normalized Shear Force

Normalized shear force was significantly influenced by the weight, carrying methods and their interaction ($p < 0.001$). Bilateral carriage of 10 lbs was the least compared to other condition. In the 10 lbs, no significant difference was found between posterior, lateral, or frontal methods. While carrying 30 lbs, both frontal and lateral methods were significantly larger than the others ($p < 0.05$). The only conditions that were insignificantly different from the baseline condition were the bilateral (*p* = 0.91), and posterior carriage of 10 lbs. (*p* = 0.233), as shown in Figure 19(b).

Normalized Moments

Normalized moment generated at the L5/S1 intervertebral disc was significantly affected by the weight, carrying method, and their interaction ($p < 0.05$). Heavier weights produced higher moment. Moreover, frontal carriage resulted in the largest moment, followed by lateral carrying method. Heavier weights exacerbated the moment during the frontal and lateral carrying methods, which were significantly different compared to the baseline ($p < 0.001$), as shown in Figure 19(c).

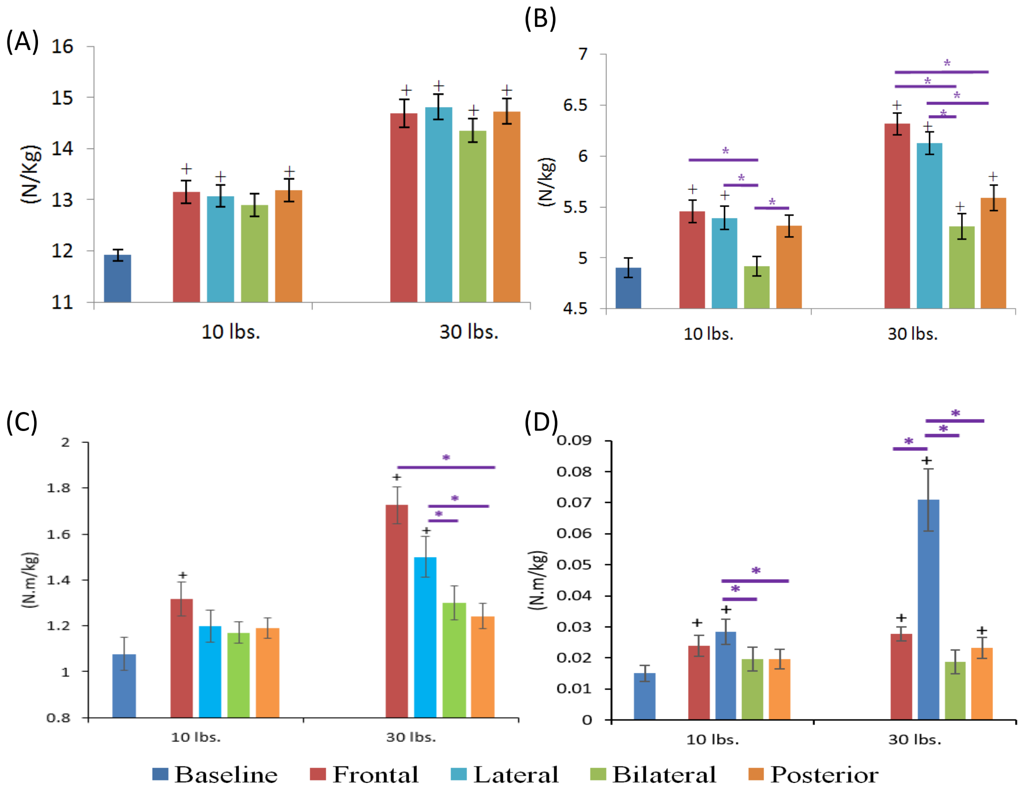


Figure 22. Mechanical loads on L5/S1: (A) Compression peak force; (B) A/P shear peak force. (C) Normalized Extension/ flexion moment. (D) Normalized lateral moment. Data are reported in terms of mean and 2 standard deviations. (+) indicates significant difference compared to the baseline. (*) indicates significant difference.

CHAPTER 5: DISCUSSION

Effect of Load Lifting on Postural Stability

The movement of the CoM is the variable that actually causes the sway of the whole body, and its components in each direction are the components of interest in studying stability. Several measures are commonly used in stability research, such as the excursion of CoM, the displacement velocity in each direction, average sway length, and the mean displacement velocity. Nevertheless, to our knowledge none of these measures evaluate stability in relation to a reference point where the optimal stability concentrates. Therefore, the aim of this paper is to define and introduce three new stability measures that evaluate sway based on the ideal spot of stability, which is the center of base of support (CBoS). Namely, deviation of CoM from CBoS in the A/P, M/L, and resultant deviation of CoM from the CBoS in the A/P, and M/L together. Moreover, a lifting experiment was conducted in order to compare the new measures with other stability measures in terms of reliability. The experiment consisted of two factors each with multiple levels. The factors were the height of the shelf and the weight of the box that will be placed on the shelf. Each participant carried a box with different weights and place it on a shelf with different heights. During carrying and placing the load, stability was calculated. To our knowledge, none of the previous research have studied the effect of task related factor on stability (i.e. measuring stability while the subject is standing and performing tasks such as lifting and placing a weight). Several stability measures were studied in this paper, and a significant effect on one or any measure implies that the stability is affected (Bhattacharya et al., 2002). The measures that were selected were commonly used in stability research. Moreover, it was expected that lifting a load will decrease stability, and working at a lower level that force the subject to change body posture will increase sway.

The height of the working surface had significant effect on all stability measures that have been investigated. It is obvious from Figures 20, the lower the working surface, the more effect will be on body stability. This result was consistent with other studies, because when a person is squatting while carrying a load (i.e. placing a load on 30" shelf height) most of the leg muscles are under high stress (Stambolian et al., 2011). Moreover, (DiDomenico, McGorry, Huang, & Blair, 2010) concluded that bent at waist, squatting, and kneeling were reported to produce threat to stability among construction workers. Additionally, (Lin & Nussbaum, 2012) studied the effects of lumbar extensor stress, and surface inclination on postural control during erect standing. The results showed that stress of lumbar extensor highly affected postural stability.

Weight lifting affected most of the stability measures significantly. Although the A/P velocity measure was not affected. This insignificant was believed because the difference between the weights is not large (i.e. 10 lb. between each level). From the Tukey's post-hoc analysis, there was a significant difference between the 25 lb. and 45 lb. weights. Clearly, the more the weight being lifted, the more effect will be on stability. These results were consistent with previous research. According to (Rugelj & Sevšek, 2011) who studied the effect of increasing load on postural sway in two types of carrying: backpack and waist jacket. The conclusion was that the sway measures of the backpack group linearly increased with additional load. Moreover, (Zultowski & Aruin, 2008) studied the effect that load magnitude, and load location have on postural sway in standing while wearing a backpack, single strapped bag, briefcase, or purse. It was concluded that an increase in load magnitude produced an increase in postural sway.

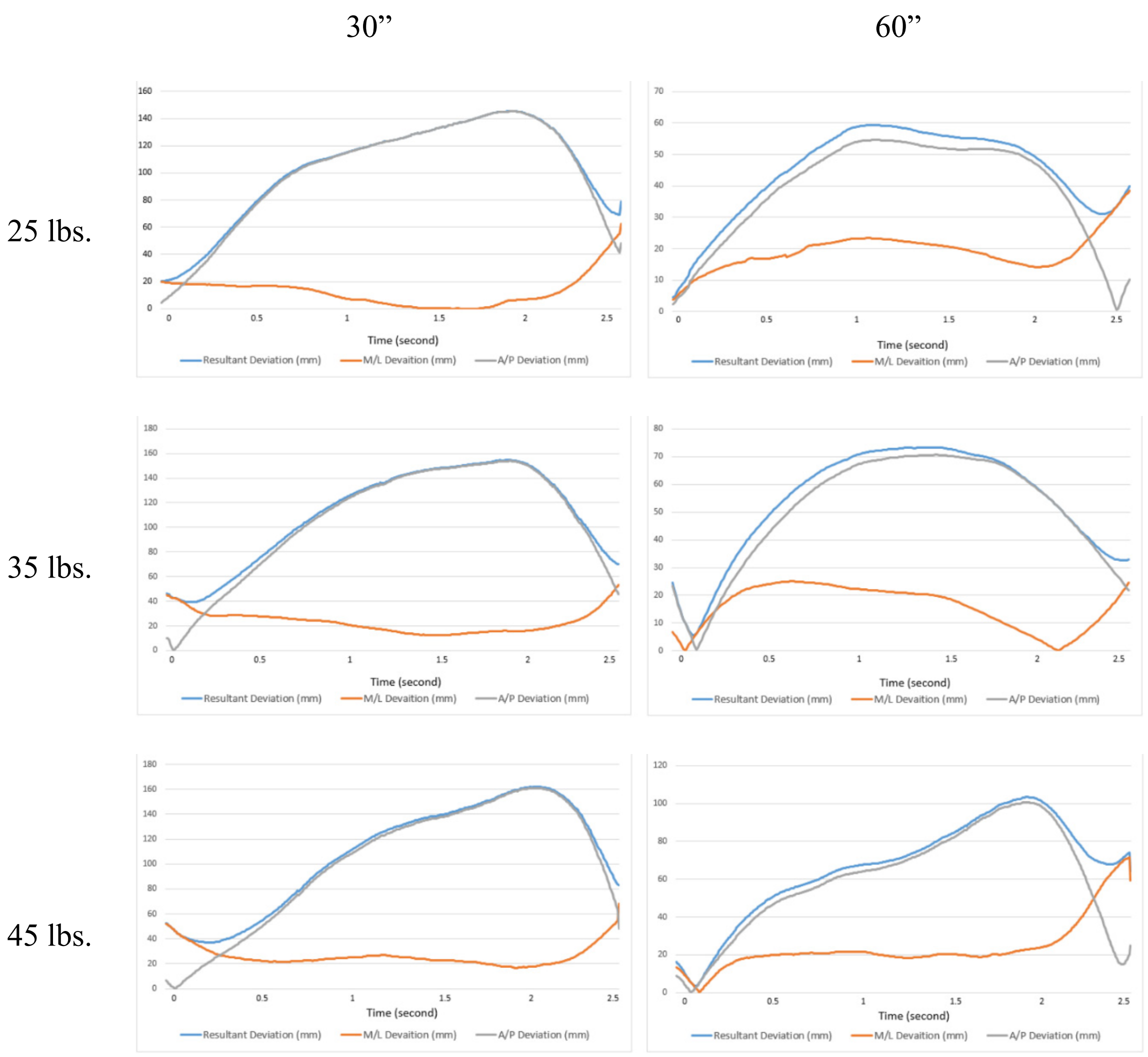


Figure 23. The effects of lifting different loads and placed on different shelf heights on postural stability.

The ICC values of the proposed measures are a clear indication of their superior reliability over the existing stability measures. The reliability of the other measures (i.e. ICC value) was similar to that reported in the literature. According to (Raymakers et al., 2005)who compared several stability measures. Each subject stood on a firm or a foam surface with eyes opened or closed. They found that the mean displacement velocity produced the smallest reproducibility error, followed by M/L excursion, and followed by A/P direction which had the largest intra-individual standardized coefficient of variation. In addition, (Nejc, Jernej, Loefler, & Kern, 2010) studied the sensitivity of individual stability measure to different stance position which were used to investigate the effect of change the size and the shape of BoS, and found that A/P, and M/L excursion had the weakest ICC (i.e. least reliability), while sway length had the strongest ICC. Nonetheless, none of the velocity measures were included in his study. Likewise, (Lafond et al., 2004)who studied the reliability of stability measures on elderly healthy people, found that the displacement velocity in each direction were more reliable than the excursions in each direction. (Lin, Seol, Nussbaum, & Madigan, 2008) examined the reliability of postural sway measures on age-related differences. They found that the resultant mean displacement velocity shows more reliability than the mean distance traveled. (Swanenburg, de Bruin, Favero, Uebelhart, & Mulder, 2008) found that the mean velocities in each direction showed more reliability than the excursions, when they measured postural balance under two conditions: standing quiet, and standing quiet and performing simple cognitive tasks (i.e. counting backwards). (Moghadam et al., 2011) determined the reliability of stability measures while the subjects were performing single and dual-task conditions and different levels of postural difficulty (i.e. rigid surface-eyes open, rigid surface-eyes closed, foam surface-eyes open, foam surface-eyes closed). They found that the mean displacement velocity was the most reliable measure among the others.

Effect of Load Carrying of Gait Stability

Another goal of this study was to investigate the effects of different weights carried with different postures on locomotion stability, gait spatio-teporal measures, and spine biomechanics. Gait stability was quantified by measuring the distance between the CoM extrapolated with its velocity (A. Hof et al., 2005) and the CBoS, a reference point inside the BoS. The CBoS changes according to the shape of the BoS, and the body is more stable when the CoM is close to the CBoS (Whiting & Rugg, 2006).

When investigating the carrying methods, it was found that frontal carriage provides the highest deviation of the XCoM from the CBoS in the A/P direction during both DS and SS phases of the gait, as shown Figure 21 for a comparison with the baseline. This could be due to the fact that, during frontal method, the A/P distance between the weight's CoM and the body's CoM is the largest among all the other carrying methods. Such carrying method resulted to be the second most unstable carrying condition in the M/L direction as well. It is likely that subjects participating to the study held the load firmly and bent their trunk sideways while walking. Such motion resulted in higher deviation of the combined CoM from the CBoS in the M/L direction (Liu et al., 2007). Lack of stability in frontal carriage forced the body to increase the cadence. This effect increased with the magnitude of the load carried, in agreement with previous studies (Myung & Smith, 1997). According to (Singh & Koh, 2009), increasing cadence allows the body weight to be rapidly transferred to the other leg in order to reduce the musculoskeletal stresses. Moreover, in order to minimize the moment generated by both the upper body and the heavy load, participants tend to decrease the length of their stride (LaFiandra, Holt, Wagenaar, & Obusek, 2002). This result is in an agreement with (Myung & Smith, 1997). However, in order to have adequate BoS area to prevent falling with a short stride length, participant kept their step width unchanged (i.e. similar to the baseline). As similarly observed in previous studies (A. Anderson et al., 2007; Fiolkowski, Horodyski, Bishop, Williams, & Stylianou, 2006), trunk extension and lateral bending were an adaptive strategies implemented by the participants to counterbalance the moment generated by the weight carried frontally and to restore the combined CoM to its original location. These trunk adjustments resulted in higher A/P shear force on the L5/S1 disc than bilateral and posterior methods, in agreement with (Rohlmann, Zander, Graichen, Schmidt, & Bergmann, 2014).

Lateral carriage resulted in the second most unstable condition of load carriage. As a compensation phenomenon, participants tended to flex their trunk while walking in order to counterbalance the weight’s effect. The degree of trunk flexion increased with the magnitude of the load. This finding is in agreement with (Fowler, Rodacki, & Rodacki, 2006). Such a compensation strategy increased the distance between the CoMs of the body and the weight carried. In terms of M/L stability, this carrying method generated the highest deviation of the XCoM from the CBoS. This findings confirms the results previously reported by (Holbein & Redfern, 1994). Lateral carriage forced the trunk to bend laterally in the opposite direction of the weight to prevent falling. This adjustment increased the distance between the combined CoM and the CBoS. As the load carried increased in magnitude, trunk bending increased and, accordingly, gait stability reduced, as shown in Figure 22 for a comparison with the baseline. Previous studies reported similar adaptive strategies (Fowler et al., 2006). Moreover, as the magnitude of the weight increased, cadence also increased to reduce the stress on the joints of the lower limb (Singh & Koh, 2009), and step with decreased. These findings are in line with the result of previous studies (Crosbie, Flynn, & Rutter, 1994; Park, Lee, & Kim, 2012; Son & Noh, 2013). Trunk adjustments in flexion and lateral bending increased the A/P shear force on the L5/S1 compared to the other carrying methods (Rohlmann et al., 2014).

Bilateral carriage was the most stable carrying method investigated. This was due to the counterbalancing effects of the weights carried by both hands which made the combined CoM to stay in its original location and close to the CBoS in all the phases of the gait. Accordingly, no significant differences were found in gait stability when compared to the baseline. Similarly, no differences were found in gait parameters with exception of the step width, which reduced. Since no trunk adjustments were observed during the bilateral carriage, this method produced the smallest forces on L5/S1.

When compared to the baseline, posterior carriage altered gait stability only in the A/P direction. This is likely due to the distance between body and weight (i.e. backpack) CoMs. However, posterior carriage still provided a superior gait stability when compared to lateral and frontal carriage methods, as previously reported (Qu, 2013). In agreement with previous investigations (D. H.-K. Chow, Hin, Ou, & Lai, 2011; Hong & Cheung, 2003; Jacobs & Golmohammad, 2003; Li, Hong, & Robinson, 2003), the degree of trunk adjustment in posterior carriage was higher than that found in lateral or frontal carriage, and this allowed the combined CoM to get closer to the CBoS. It was also found that trunk adjustment in the M/L direction only occurred in the SS phase of the gait. This was likely due to the fact that, when standing on one leg, the combined CoM deviated from the CBoS in the M/L direction. Furthermore, as the magnitude of the load carried increased, the step width became narrower. Similar results have been reported (Qu & Yeo, 2011). Overall, posterior carriage produced smaller A/P shear force when compared to frontal or lateral carriages. This result is in line with previous study (D. Chow et al., 2011).

As previously found (McGill, Marshall, & Andersen, 2013; Rohlmann et al., 2014; Rose et al., 2013; Wilke, Neef, Hinz, Seidel, & Claes, 2001), the compression force at L5/S1 increased with the magnitude of the weight carried. Notably, weight magnitude significantly affected the duration of the DS phase of the gait. Heavier weights resulted in longer duration of support by both feet during walking. This findings agree with previous research (Attwells, Birrell, Hooper, & Mansfield, 2006; Birrell & Haslam, 2009; Demura, Demura, & Shin, 2010; Goh, Thambyah, & Bose, 1998). As the load increases, stride length decreases, which results in higher DS duration to provide better stability (Polcyn, Bensel, Harman, Obusek, & Pandorf, 2002). An increase in DS duration decreases the musculoskeletal stress on the joints of the lower limb (Kinoshita, 1985). Interestingly, as the stride length decreased, also the cadence increased. Therefore, similar to what reported in previous studies (Crosbie et al., 1994; Crowe, Schiereck, & Keessen, 1993; DeVita, Hong, & Hamill, 1992; Goh et al., 1998; Hong & Cheung, 2003), walking speed did not change in any condition investigated. Moreover, carrying methods with larger moment arm around the L5/S1 disc, such as frontal and lateral, generated the highest extension/ flexion and lateral moments compared to the other methods.

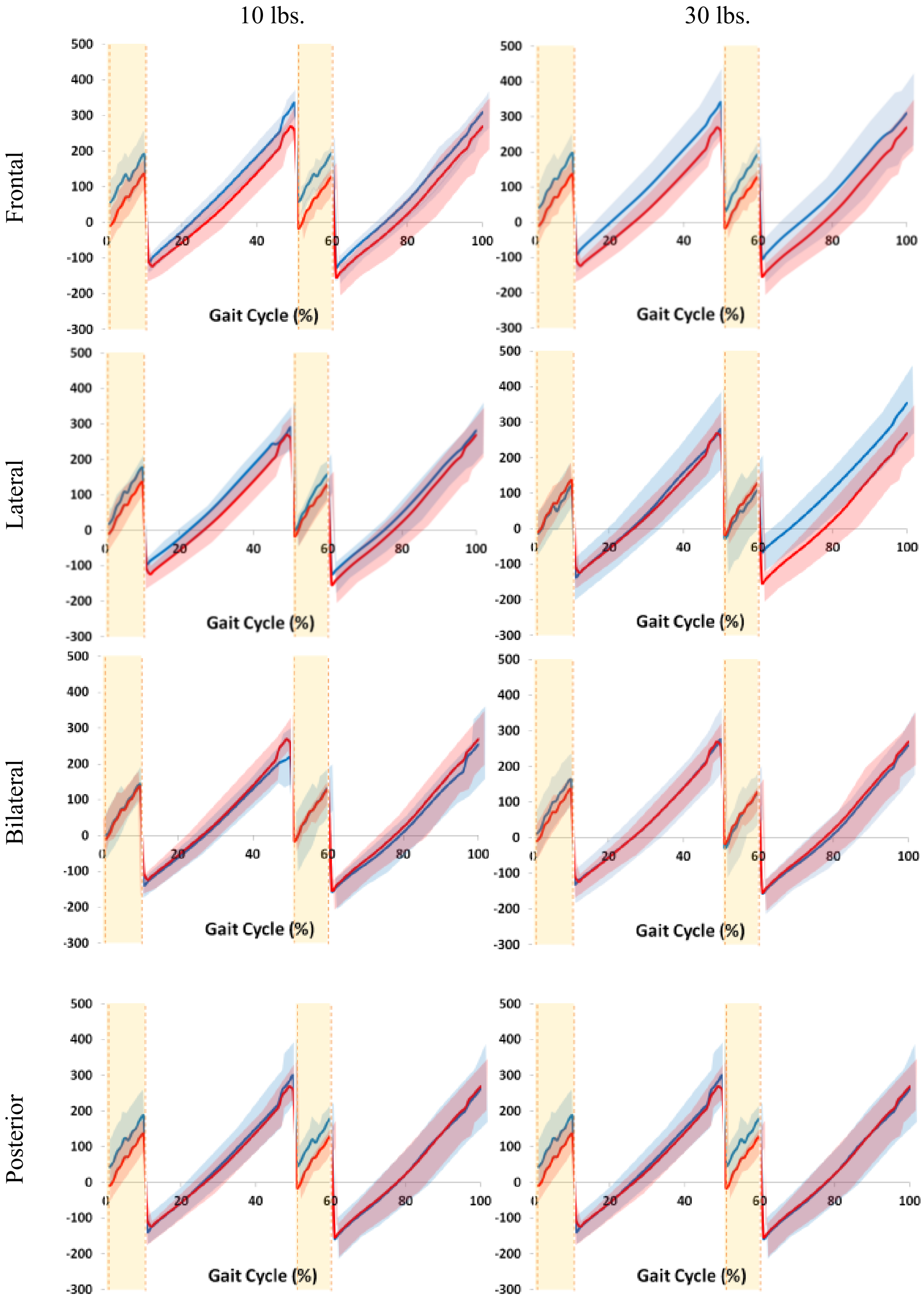


Figure 24. Deviation of the XCoM from the CBoS throughout the gait cycle in the A/P direction of the baseline (red curve) and frontal carriage of 30 lbs (blue curve); Shaded curves represent mean ± 1 standard deviation. Yellow blocks represents DS phase. –ve values indicate that XCoM is located posteriorly from the CBoS. +ve values indicate that XCoM is located anteriorly from the CBoS.

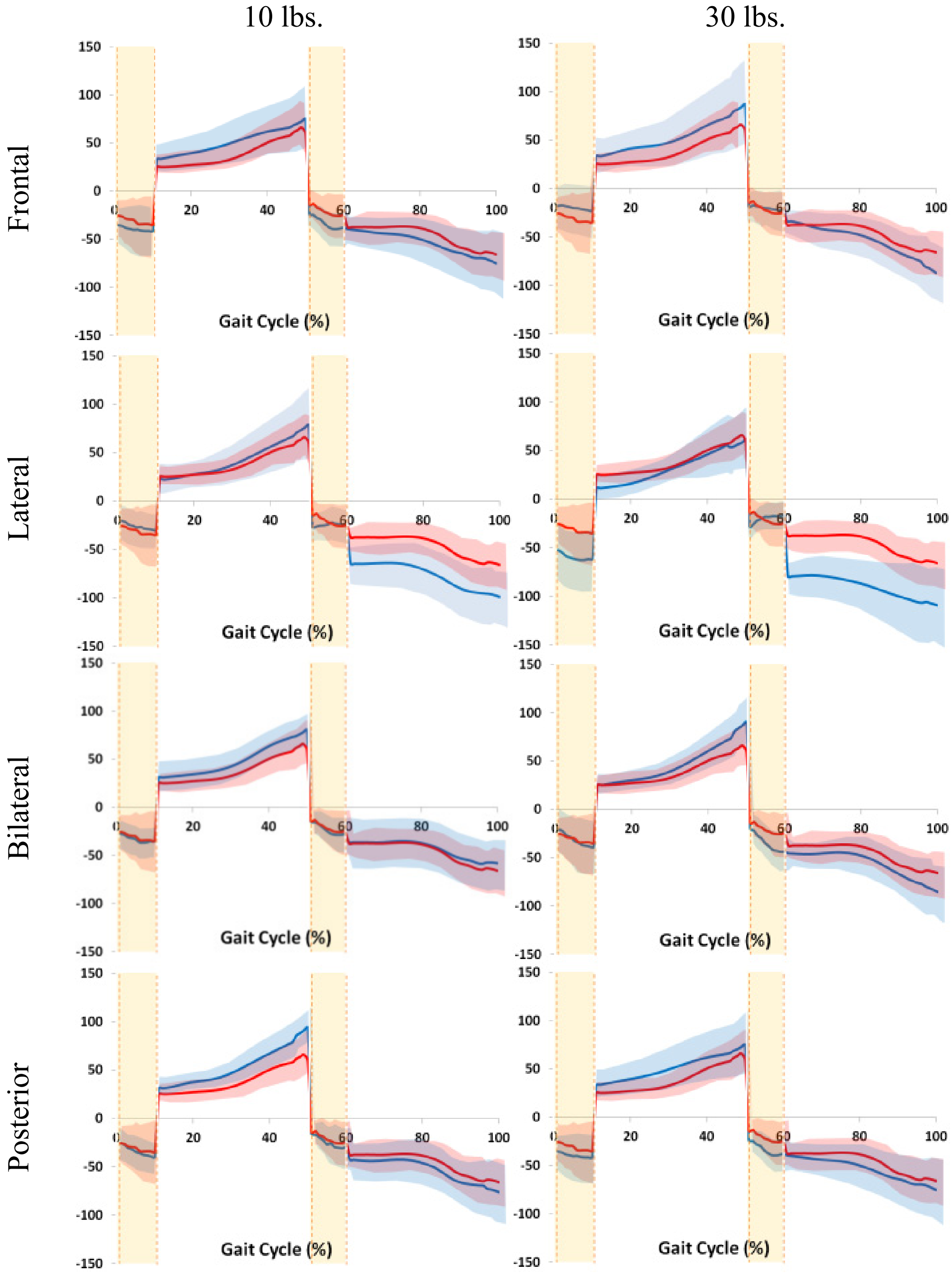


Figure 25. Deviation of the XCoM from the CBoS throughout the gait cycle in the M/L direction of the baseline (red curve) and frontal carriage of 30 lbs (blue curve); Shaded curves represent mean ± 1 standard deviation. Yellow blocks represents DS phase. –ve values indicate that XCoM is located on the left to CBoS. +ve values indicate that XCoM is located on the right to CBoS.

Limitations and Future Studies

Several limitations in this study should be discussed. First, loads carried in this study were characterized by a regular shape and presented ergonomic handles. In the work environment, workers may be carrying objects of irregular shapes, and may not present ergonomic handles. For example, large objects force the subject to adopt distressing postures that affect the kinematics of the body, which in turns will destabilize the human body (Birrell & Haslam, 2010). Further studies should be conducted while testing postural and gait stability when carrying irregular objects. Second, this study only examined load lifting and carrying on level surface. Working on irregular surfaces, such as inclined or slippery surfaces, alter the spatio-temproal gait parameters (Bunterngchit, Lockhart, Woldstad, & Smith, 2000; Grönqvist, 1999). These types of alteration increase the chances of falls and slips (Cham & Redfern, 2004; Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001). Therefore, it is expected that load carriages while walking on different surfaces would exacerbate instability. Third, participants of the current study were only young healthy adults. According to the (U.S. Department of Labor, 2016), 52% of the total workforce in the US are 20 – 44 y.o. and 44% are 45 years and over. Older subjects might be less stable in gait (Iosa, Fusco, Morone, & Paolucci, 2014). Therefore, the results of this study should be considered as a best case scenario, and one would anticipate the increase in the potential risks associated with less fit or older population.

CHAPTER 6: CONCLUSIONS

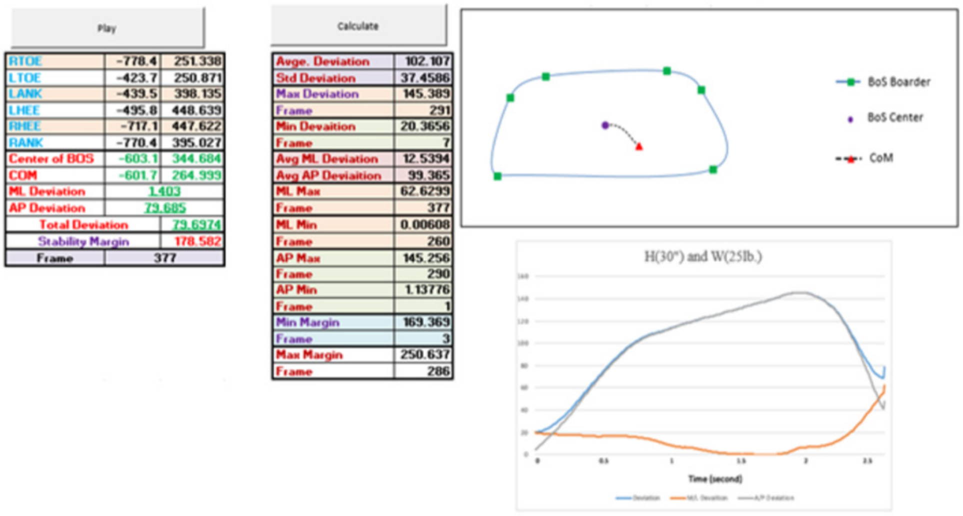
In this study, the effect of manual material lifting and carrying tasks on body stability were investigated. Postural and dynamic stability were measured using new stability measures that were introduced in this study. A point inside the BoS, which represents the optimal location of stability (i.e. CBoS), was the reference point for quantifying stability. Postural stability was measured by finding the deviation of the body's CoM from the CBoS. Using the proposed measures, the effect of lifting task on postural stability was investigated. Manual material lifting of heavy weights significantly destabilized the human body in both directions. Moreover, the heights of the working surfaces that force the body to be changed from the upright gesture exacerbated the effect on postural stability. Therefore, it is recommended that, whenever possible, the working surface during lifting tasks to be at elbow height in order to keep the upright posture of the human body.

In addition, this study adds to the knowledge used for designing manual material carrying tasks from the perspective of locomotion stability, gait measures and loads at the lumbar spine. Gait stability was measured by finding the deviation between the CBoS and the CoM extrapolated with its velocity. Frontal and lateral methods generated the most unstable conditions in the A/P and M/L when compared to the other carrying methods. The unstable locomotion forced the gait parameters to be altered in order to maintain stability. Additionally, the postures maintained in these conditions resulted in significantly high compression, shear forces, moments acting on the L5/S1 disc. To reduce the potential risks associated with falling or overloading the lumbar spine, whenever possible, loads carried should be carried bilaterally or posteriorly.

Appendix

Stability Code

A custom Visual Basic Application (VBA) code was developed in order to calculate the proposed measures. First, the user will enter the coordinates of the BoS that were captured from the motion capturing system. Second, the user will input the height of the feet markers from the ground. This will assure that the code will eliminate any marker that leaves the ground, and deform the BoS. Then, the program will calculate the CBoS at each frame. Then, the user will enter the coordinates of the CoM that were recorded from the motion capturing system. After clicking "OK", the code will calculate all the proposed measures. Moreover, a chart will be drawn that let the user observe how the CoM deviated from the CBoS instantaneously. The CoM deviation will be presented as video. Another chart will show how the measures were altered in a specific period of time, as shown below. The code is available upon request.



RTOE	-778.4	251.338
LTOE	-423.7	250.871
LANK	-439.5	398.135
LHEE	-495.8	448.639
RHEE	-717.1	447.622
RANK	-770.4	395.027
Center of BOS	-603.1	344.684
COM	-601.7	264.999
ML Deviation	1.403	
AP Deviation	79.685	
Total Deviation		79.6974
Stability Margin		178.582
Frame	377	

Avge. Deviation	102.107
Std Deviation	37.4586
Max Deviation	145.389
Frame	291
Min Devaition	20.3656
Frame	7
Avg ML Deviation	12.5394
Avg AP Deviaition	99.365
ML Max	62.6299
Frame	377
ML Min	0.00608
Frame	260
AP Max	145.256
Frame	290
AP Min	1.13776
Frame	1
Min Margin	169.369
Frame	3
Max Margin	250.637
Frame	286

Figure A – 1. The output of the stability code

Randomized Treatments Order

The randomized order of the effect of load carrying on gait stability is as follow:

Where,

A: 10 lb. load weight.

B: 20 lb. load weight.

1: Anterior symmetric carrying at elbow. 4: Lateral asymmetric carrying at knuckle.

2: Anterior asymmetric carrying at elbow. 5: Posterior carrying at waist.

3: Lateral symmetric carrying at knuckle. 6: Posterior carrying at shoulder.

Since the posterior carrying might require detaching the pelvic markers, the four posterior carrying treatments will be performed back to back. Half of the sample size will perform them in the beginning, and the other half will perform them at the end, in order to eliminate the effect of fatigue.

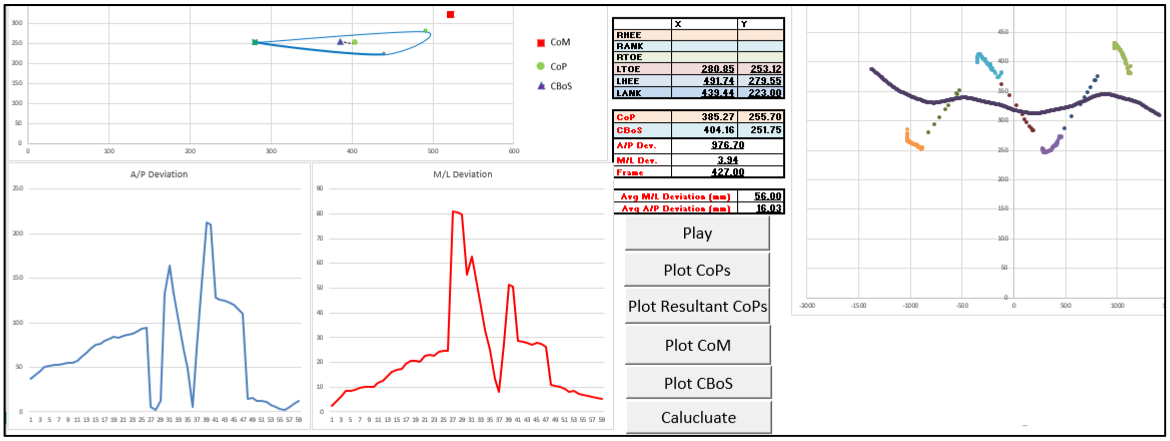
		Trial											
		1	2	3	4	5	6	7	8	9	10	11	12
Subject	1	A,6	B,6	A,5	B,5	A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4
		B,5	A,6	A,5	B,6	B,4	B,3	B,1	A,3	A,4	B,2	A,2	A,1
		B,5	B,6	A,6	A,5	B,1	A,1	A,2	B,4	A,4	B,2	A,3	B,3
	2	B,6	A,5	B,5	A,6	B,2	A,2	B,1	B,3	A,3	A,1	B,4	A,4
		A,5	B,6	B,5	A,6	A,4	B,4	A,1	B,1	A,2	A,3	B,2	B,3
		A,6	B,6	A,5	B,5	B,1	A,3	B,3	A,4	A,1	B,4	A,2	B,2
	3	B,5	B,6	A,6	A,5	B,1	A,1	A,2	B,4	A,4	B,2	A,3	B,3
		A,5	B,6	B,5	A,6	A,3	A,4	B,3	A,1	A,2	B,1	B,2	B,4
		A,6	A,5	B,6	B,5	B,4	A,4	B,2	A,3	A,2	A,1	B,1	B,3
	4	A,6	B,6	A,5	B,5	B,1	A,3	B,3	A,4	A,1	B,4	A,2	B,2
		B,5	A,5	B,6	A,6	B,2	B,1	A,3	B,4	A,4	A,2	A,1	B,3
		A,5	B,6	B,5	A,6	A,3	A,4	B,3	A,1	A,2	B,1	B,2	B,4
	5	A,5	B,6	B,5	A,6	A,4	B,4	A,1	B,1	A,2	A,3	B,2	B,3
		A,5	A,6	B,5	B,6	A,3	A,1	B,2	B,1	B,4	B,3	A,2	A,4
		B,5	B,6	A,5	A,6	A,2	A,1	B,3	A,3	B,2	A,4	B,4	B,1
	6	A,5	B,6	A,6	B,5	B,2	A,1	A,2	A,4	B,3	B,1	B,4	A,3

		A,6	B,6	A,5	B,5	A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4
		B,5	B,6	A,6	A,5	B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3
	7	A,6	A,5	B,6	B,5	B,4	A,4	B,2	A,3	A,2	A,1	B,1	B,3
		A,6	B,6	B,5	A,5	B,3	A,2	B,2	A,4	A,1	A,3	B,4	B,1
		A,5	A,6	B,5	B,6	A,3	A,1	B,2	B,1	B,4	B,3	A,2	A,4
	8	A,5	B,6	B,5	A,6	A,3	A,4	B,3	A,1	A,2	B,1	B,2	B,4
		B,6	A,5	B,5	A,6	B,2	A,2	B,1	B,3	A,3	A,1	B,4	A,4
		B,5	B,6	A,6	A,5	B,1	A,1	A,2	B,4	A,4	B,2	A,3	B,3
	9	B,5	A,6	B,6	A,5	A,3	A,4	A,2	B,3	B,2	A,1	B,4	B,1
		B,6	B,5	A,6	A,5	B,3	A,4	A,2	B,2	B,1	B,4	A,1	A,3
		B,5	B,6	A,6	A,5	A,1	A,2	A,4	A,3	B,1	B,2	B,4	B,3
	10	A,5	A,6	B,5	B,6	B,3	A,3	B,4	A,4	A,1	B,2	A,2	B,1
		B,6	A,6	A,5	B,5	A,3	B,1	A,2	B,4	A,1	B,3	B,2	A,4
		B,5	B,6	A,5	A,6	B,3	A,2	B,2	A,4	A,1	A,3	B,4	B,1
	11	B,6	A,6	A,5	B,5	A,1	B,4	B,2	B,1	B,3	A,4	A,2	A,3
		B,5	A,6	A,5	B,6	B,4	B,3	B,1	A,3	A,4	B,2	A,2	A,1
		A,6	B,6	A,5	B,5	A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4
	12	B,5	B,6	A,5	A,6	A,3	B,4	B,3	A,4	B,2	B,1	A,1	A,2
		B,5	B,6	A,6	A,5	B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3
		B,5	B,6	A,5	A,6	A,2	A,1	B,3	A,3	B,2	A,4	B,4	B,1
	13	B,5	A,5	B,6	A,6	B,2	B,1	A,3	B,4	A,4	A,2	A,1	B,3
		A,5	B,6	A,6	B,5	A,1	A,3	B,2	A,4	B,3	B,4	B,1	A,2
		A,6	A,5	B,6	B,5	B,3	A,4	B,2	A,1	B,4	B,1	A,3	A,2
	14	B,6	A,5	A,6	B,5	B,3	A,3	B,1	A,4	A,1	B,2	A,2	B,4
		A,6	B,6	A,5	B,5	A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4
		A,6	B,6	A,5	B,5	B,1	A,3	B,3	A,4	A,1	B,4	A,2	B,2
	15	A,6	B,6	A,5	B,5	B,2	A,4	A,3	B,3	B,4	A,1	B,1	A,2
		A,5	B,6	B,5	A,6	B,2	A,4	A,1	A,3	B,4	B,1	B,3	A,2
		B,5	A,6	B,6	A,5	B,1	A,3	A,4	B,2	A,2	A,1	B,4	B,3
	16	A,3	A,1	B,2	B,1	B,4	B,3	A,2	A,4	A,5	A,6	B,5	B,6
		B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3	B,5	B,6	A,6	A,5
		A,2	A,1	B,3	A,3	B,2	A,4	B,4	B,1	B,5	B,6	A,5	A,6
	17	B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3	B,5	B,6	A,6	A,5
		B,3	A,3	A,4	A,1	A,2	B,2	B,1	B,4	A,5	A,6	B,5	B,6
		A,3	A,1	B,4	B,2	A,2	B,1	B,4	B,3	B,5	B,6	A,6	A,5
	18	A,2	A,1	B,3	A,3	B,2	A,4	B,4	B,1	B,5	B,6	A,5	A,6
		B,4	A,2	B,2	B,1	A,3	B,3	A,4	A,1	A,6	B,6	A,5	B,5
		B,1	B,3	A,3	A,4	A,1	B,4	A,2	B,2	A,5	A,6	B,5	B,6
	19	A,2	A,3	A,1	B,3	B,1	A,4	B,4	B,2	A,6	A,5	B,6	B,5

		B,4	A,1	A,4	B,1	B,2	A,2	A,3	B,3	A,6	B,6	A,5	B,5
		A,3	A,4	B,3	A,1	A,2	B,1	B,2	B,4	A,5	B,6	B,5	A,6
	20	A,1	A,3	B,2	A,4	B,3	B,4	B,1	A,2	A,5	A,6	B,6	B,5
		B,4	B,1	B,3	A,2	B,2	A,4	A,1	A,3	B,5	A,6	B,6	A,5
		B,4	B,3	B,1	A,3	A,4	B,2	A,2	A,1	B,5	A,6	A,5	B,6
	21	B,3	A,4	B,2	A,1	B,4	B,1	A,3	A,2	B,6	A,6	B,5	A,5
		A,3	B,3	A,4	A,2	B,2	B,1	B,4	A,1	A,6	B,6	B,5	A,5
		A,3	A,4	B,3	A,1	A,2	B,1	B,2	B,4	A,5	B,6	B,5	A,6
	22	A,4	A,2	A,1	B,3	B,2	A,3	B,1	B,4	A,5	B,5	A,6	B,6
		B,2	A,2	A,1	B,4	B,3	B,1	A,3	A,4	B,5	B,6	A,6	A,5
		B,4	B,3	B,1	A,3	A,4	A,2	A,1	B,2	B,6	A,5	B,5	A,6
	23	B,3	A,4	A,2	B,1	B,2	A,1	B,4	A,3	B,6	A,5	A,6	B,5
		B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3	B,5	B,6	A,6	A,5
		A,4	A,3	B,1	B,3	B,2	A,1	B,4	A,2	B,5	A,6	B,6	A,5
	24	B,4	A,1	A,3	B,3	A,4	A,2	B,2	B,1	B,6	B,5	A,6	A,5
		A,2	A,3	A,1	B,3	B,1	A,4	B,4	B,2	A,6	A,5	B,6	B,5
		B,2	B,4	B,3	A,1	A,2	A,4	A,3	B,1	B,5	B,6	A,6	A,5
	25	B,2	B,4	B,3	A,1	A,2	A,4	A,3	B,1	B,5	B,6	A,6	A,5
		A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4	A,6	B,6	A,5	B,5
		A,4	A,2	A,1	B,3	B,2	A,3	B,1	B,4	A,5	B,5	A,6	B,6
	26	A,3	B,3	B,4	A,1	A,4	B,1	B,2	A,2	B,6	A,5	B,5	A,6
		B,1	A,1	A,2	B,4	A,4	B,2	A,3	B,3	B,5	B,6	A,6	A,5
		B,3	A,3	B,4	A,4	A,1	B,2	A,2	B,1	A,5	A,6	B,5	B,6
	27	B,3	B,4	B,1	B,2	A,4	A,1	A,2	A,3	A,6	B,6	B,5	A,5
		B,4	A,3	A,4	A,1	B,2	A,2	B,1	B,3	B,5	B,6	A,6	A,5
		A,3	A,4	A,2	B,3	B,2	A,1	B,4	B,1	B,5	A,6	B,6	A,5
	28	A,3	B,1	A,2	B,4	A,1	B,3	B,2	A,4	B,5	A,6	B,6	A,5
		A,4	A,2	A,1	B,3	B,2	A,3	B,1	B,4	A,5	B,5	A,6	B,6
		B,4	A,4	B,2	A,3	A,2	A,1	B,1	B,3	A,6	A,5	B,6	B,5
	29	B,3	A,2	B,2	A,4	A,1	A,3	B,4	B,1	A,6	B,6	B,5	A,5
		A,2	B,2	B,1	B,3	A,3	A,4	A,1	B,4	A,6	B,6	A,5	B,5
		A,1	A,3	B,2	A,4	B,3	B,4	B,1	A,2	A,5	A,6	B,6	B,5
	30	B,4	B,3	B,1	A,3	A,4	B,2	A,2	A,1	B,5	A,6	A,5	B,6
		A,3	B,1	A,2	B,4	A,1	B,3	B,2	A,4	B,5	A,6	B,6	A,5
		A,2	A,3	A,1	B,3	B,1	A,4	B,4	B,2	A,6	A,5	B,6	B,5

Stability VBA Code

A custom Visual Basic Application (VBA) code was developed in order to calculate the proposed measures. First, the user will enter the coordinates of the BoS that were captured from the motion capturing system. Second, the user will input the height of the feet markers from the ground. This will assure that the code will eliminate any marker that leaves the ground, and deform the BoS. Then, the program will calculate the CBoS at each frame. Then, the user will enter the coordinates of the CoM, and the CoP that were recorded from the motion capturing system. Then, if 2 feet were on two force plates, the code will find the net force and cet CoP. After clicking “OK”, the code will calculate all the proposed measures. Moreover, a chart will be drawn that let the user observe how the CoM, and CoP deviated from the CBoS instantaneously. The CoM, and CoP deviation will be presented as video. Another chart will show how the measures were altered in a specific period of time, as shown below. The code is available upon request.



	X	Y
RHEE		
RANK		
RTOE		
LTOE	280.85	253.12
LHEE	491.74	279.55
LANK	439.44	223.00

CoP	385.27	255.70
CBoS	404.16	251.75
A/P Dev.	976.70	
M/L Dev.	3.94	
Frame	427.00	

Avg M/L Deviation (mm)	56.00
Avg A/P Deviation (mm)	16.03

Figure A – 2.VBA Stability Code

A. Removing all the markers that deform the BoS

```
Sub MaxHeight()
' Macro1 Macro
Dim fem As Integer
Dim maxz As Integer
frm = Cells(1, 39).Value
i = 3
maxrheel = Cells(1, 32).Value
maxrtoe = Cells(2, 32).Value
maxrankle = Cells(3, 32).Value
maxrmt5 = Cells(4, 32).Value
maxlheel = Cells(1, 34).Value
maxltoe = Cells(2, 34).Value
maxlankle = Cells(3, 34).Value
maxlmt5 = Cells(4, 34).Value
While i <= frm
' marker 1 LANK
If Cells(i, 4) > maxlankle Then
Cells(i, 2).Value = ""
Cells(i, 3).Value = ""
Else
Cells(i, 2).Value = Cells(i, 2).Value
Cells(i, 3).Value = Cells(i, 3).Value
End If
' marker 2 LHEE
If Cells(i, 7) > maxlheel Then
Cells(i, 5).Value = ""
Cells(i, 6).Value = ""
Else
Cells(i, 5).Value = Cells(i, 5).Value
```

```
Cells(i, 6).Value = Cells(i, 6).Value
End If
'marker 3 LTOE
If Cells(i, 10) > maxltoe Then
Cells(i, 8).Value = ""
Cells(i, 9).Value = ""
Else
Cells(i, 8).Value = Cells(i, 8).Value
Cells(i, 9).Value = Cells(i, 9).Value
End If
'marker 4 L5
If Cells(i, 13) > maxlmt5 Then
Cells(i, 11).Value = ""
Cells(i, 12).Value = ""
Else
Cells(i, 11).Value = Cells(i, 11).Value
Cells(i, 12).Value = Cells(i, 12).Value
End If
'marker 5 RANK
If Cells(i, 16) > maxrankle Then
Cells(i, 14).Value = ""
Cells(i, 15).Value = ""
Else
Cells(i, 14).Value = Cells(i, 14).Value
Cells(i, 15).Value = Cells(i, 15).Value
End If
'marker 6 RHEE
If Cells(i, 19) > maxrheel Then
Cells(i, 17).Value = ""
Cells(i, 18).Value = ""
```

```
Else
Cells(i, 17).Value = Cells(i, 17).Value
Cells(i, 18).Value = Cells(i, 18).Value
End If
'marker 7 RTOE
If Cells(i, 22) > maxrtoe Then
Cells(i, 20).Value = ""
Cells(i, 21).Value = ""
Else
Cells(i, 20).Value = Cells(i, 20).Value
Cells(i, 21).Value = Cells(i, 21).Value
End If
'marker 8 R5MT
If Cells(i, 25) > maxrmt5 Then
Cells(i, 23).Value = ""
Cells(i, 24).Value = ""
Else
Cells(i, 23).Value = Cells(i, 23).Value
Cells(i, 24).Value = Cells(i, 24).Value
End If
i = i + 1
Wend
End Sub
```

B. Find the CBoS

```
Sub FindCBoS()
Dim maxfrm As Integer
maxfrm = Cells(1, 39).Value
i = 4
j = 4
Sheets("Sheet2").Select
```

```
While i <= maxfrm
    Range(Cells(i, 2), Cells(i, 3)).Select
    Selection.Copy
    Range("AE7").Select
    ActiveSheet.Paste
    Range(Cells(i, 5), Cells(i, 6)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AG7").Select
    ActiveSheet.Paste
    Range(Cells(i, 8), Cells(i, 9)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AI7").Select
    ActiveSheet.Paste
    Range(Cells(i, 11), Cells(i, 12)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AK7").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range(Cells(i, 14), Cells(i, 15)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AM7").Select
    ActiveSheet.Paste
    Range(Cells(i, 17), Cells(i, 18)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AO7").Select
```

```
    ActiveSheet.Paste
    Range(Cells(i, 20), Cells(i, 21)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AQ7").Select
    ActiveSheet.Paste
    Range(Cells(i, 23), Cells(i, 24)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("AS7").Select
    ActiveSheet.Paste
    Range("AM13:AO13").Select
    Application.CutCopyMode = False
    Selection.Copy
    Sheets("Sheet1").Select
    Cells(j, 4).Select
    Selection.PasteSpecial Paste:=xlPasteValues,
Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
       Sheets("Sheet2").Select
i = i + 1
j = j + 1
Application.ScreenUpdating = False
Wend
End Sub
```

C. Calculate the XCoM

```
Sub Vel_XCoM()
maxfrme = Cells(1, 2).Value
i = 5
While i <= maxfrme
```

```
Cells(i, 8).Value = (Cells(i, 4).Value) + (Cells(i,
6).Value / Sqr(Cells(1, 7).Value / Cells(1, 9).Value))

Cells(i, 9).Value = (Cells(i, 5).Value) + (Cells(i,
7).Value / Sqr(Cells(1, 7).Value / Cells(1, 9).Value))

i = i + 1

Wend

End Sub
```

D. Find the deviation of the XCoM from the CBoS

```
Sub Macro2()

maxfrme = Cells(1, 2).Value

a1 = Cells(2, 25).Value + 3

b1 = Cells(2, 26).Value + 3

a2 = Cells(3, 25).Value + 3

b2 = Cells(3, 26).Value + 3

i = a1 + 1

While i <= maxfrme + 3

'XCoM - CboS

Cells(i, 34).Value = Abs(Cells(i, 8).Value - Cells(i,
12).Value)

Cells(i, 35).Value = Abs(Cells(i, 9).Value - Cells(i,
13).Value)

i = i + 1

Wend

Cells(23, 41).Value =
Application.WorksheetFunction.Max(Range(Cells(a1 + 1,
34), Cells(b1, 34)))

Cells(24, 41).Value =
Application.WorksheetFunction.Max(Range(Cells(b1 + 1,
34), Cells(a2 - 1, 34)))

Cells(25, 41).Value =
Application.WorksheetFunction.Max(Range(Cells(a2, 34),
Cells(b2, 34)))
```

```
Cells(26, 41).Value =
Application.WorksheetFunction.Max(Range(Cells(b2 + 1,
34), Cells(maxfrme + 3, 34)))

Cells(23, 42).Value =
Application.WorksheetFunction.Max(Range(Cells(a1 + 1,
35), Cells(b1, 35)))

Cells(24, 42).Value =
Application.WorksheetFunction.Max(Range(Cells(b1 + 1,
35), Cells(a2 - 1, 35)))

Cells(25, 42).Value =
Application.WorksheetFunction.Max(Range(Cells(a2, 35),
Cells(b2, 35)))

Cells(26, 42).Value =
Application.WorksheetFunction.Max(Range(Cells(b2 + 1,
35), Cells(maxfrme + 3, 35)))

Cells(23, 40).Value =
Application.WorksheetFunction.Max(Range(Cells(a1 + 1,
36), Cells(b1, 36)))

Cells(24, 40).Value =
Application.WorksheetFunction.Max(Range(Cells(b1 + 1,
36), Cells(a2 - 1, 36)))

Cells(25, 40).Value =
Application.WorksheetFunction.Max(Range(Cells(a2, 36),
Cells(b2, 36)))

Cells(26, 40).Value =
Application.WorksheetFunction.Max(Range(Cells(b2 + 1,
36), Cells(maxfrme + 3, 36)))

End Sub
```

E. Plot the results and play it simultaneously

```
Sub Macro11()

i = Cells(5, 15).Value

j = Cells(5, 16).Value

' number of frames times 8

While i <= 6880

     ActiveSheet.ChartObjects("Chart 1").Activate

     ActiveChart.SetSourceData Source:=Range(Cells(i,
     3), Cells(i + 8, 4))
```

```
          i = i + 9
          j = j + 9
          Cells(1, 1).Value = ii
          ii = ii + 1
          Application.Wait Now + TimeSerial(0, 0, 1 / 4)
          Cells(4, 15).Value = i
          Cells(4, 16).Value = j
     Wend
End Sub
```

Statistical Analysis

This section includes all the important details of the statistical analysis. For each dependent variable, first it was compared with the baseline condition using Tukey's post-hoc test. Second, the two-way repeated measures ANOVA followed by Tukey's post-hoc test are shown. Finally, the 4 in 1 residuals plots are shown in order to illustrate that the assumptions of the repeated measures ANOVA were satisfied. Namely, normality, independency and sphericity.

XCoM deviation in the A/P direction during Double Support phases (mm)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	58.42	6.48	(38.31, 78.53)	9.02	0.000
F30 - Baseline	60.54	6.48	(40.43, 80.65)	9.35	0.000
L10 - Baseline	32.51	6.48	(12.41, 52.62)	5.02	0.000
L30 - Baseline	54.73	6.48	(34.62, 74.84)	8.45	0.000
B10 - Baseline	17.54	6.48	(-2.57, 37.65)	2.71	0.145
B30 - Baseline	29.13	6.48	(9.02, 49.24)	4.50	0.000
P10 - Baseline	45.78	6.48	(25.67, 65.89)	7.07	0.000
P30 - Baseline	51.79	6.48	(31.69, 71.90)	8.00	0.000

Analysis of Variance

```
Source                        DF   Adj SS   Adj MS  F-Value  P-Value
  Carrying Method              3   125477  41825.8    42.50    0.000
  Load (lbs)                   1    19381  19381.2    19.69    0.000
  Carrying Method*Load (lbs)   3     9915   3305.2     3.36    0.018
  Subject                     29   644890  22237.6    22.59    0.000
Error                        683   672201    984.2
Total                        719  1471865
```

Tukey's Post-hoc Analysis

Weight (W)

```
30     360  505.405  A
10     360  495.029         B
```

Carrying Method (C)	Frontal	180	516.382	A
	Posterior	180	504.887	B
	Lateral	180	499.723	B
	Bilateral	180	479.876	C
W x C	Frontal 30	90	517.664	A
	Frontal 10	90	515.100	A B
	Lateral 30	90	510.831	A B
	Posterior 30	90	507.895	A B
	Posterior 10	90	501.879	B C
	Lateral 10	90	488.615	C D
	Bilateral 30	90	485.232	D
	Bilateral 10	90	474.521	D

XCoM deviation in the A/P direction during Single Support phases (mm)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	59.91	7.96	(35.20, 84.62)	7.53	0.000
F30 - Baseline	60.63	7.96	(35.92, 85.34)	7.62	0.000
L10 - Baseline	34.25	7.96	(9.54, 58.96)	4.30	0.001
L30 - Baseline	35.40	7.96	(10.68, 60.11)	4.45	0.000
B10 - Baseline	14.94	7.96	(-9.77, 39.65)	1.88	0.630
B30 - Baseline	18.63	7.96	(-6.08, 43.34)	2.34	0.318
P10 - Baseline	24.87	7.96	(0.16, 49.59)	3.12	0.047
P30 - Baseline	39.40	7.96	(14.69, 64.11)	4.95	0.000

Analysis of Variance

```
Source                         DF   Adj SS  Adj MS  F-Value  P-Value
  Carrying Method               3   161400   53800    46.50    0.000
  Load (lbs)                    1     5294    5294     4.58    0.033
  Carrying Method*Load (lbs)    3     4275    1425     1.23    0.297
  Subject                      29  1206822   41615    35.97    0.000
Error                         683   790211    1157
Total                         719  2168001
```

Tukey's Post-hoc Analysis

Weight (W)

```
30     360  681.240  A
10     360  675.817         B
```

Carrying Method (C)

```
Frontal     180  701.760  A
Lateral     180  677.172      B
Posterior   180  675.204      B
Bilateral   180  659.979         C
```

W x C

```
Interaction is insignificant
```

XCoM deviation in the M/L direction during Double Support phases (mm)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	7.18	2.14	(0.54, 13.83)	3.36	0.022
F30 - Baseline	8.56	2.14	(1.91, 15.20)	4.00	0.002
L10 - Baseline	11.28	2.14	(4.63, 17.92)	5.27	0.000
L30 - Baseline	33.42	2.14	(26.78, 40.07)	15.62	0.000
B10 - Baseline	2.47	2.14	(-4.17, 9.11)	1.15	0.966
B30 - Baseline	3.98	2.14	(-2.66, 10.62)	1.86	0.642
P10 - Baseline	5.07	2.14	(-1.58, 11.71)	2.37	0.302
P30 - Baseline	6.55	2.14	(-0.09, 13.19)	3.06	0.057

Analysis of Variance

```
Source                         DF  Adj SS   Adj MS  F-Value  P-Value
  Carrying Method               3   44196  14732.1    98.08    0.000
  Load (lbs)                    1    9309   9309.4    61.98    0.000
  Carrying Method*Load (lbs)    3   15266   5088.7    33.88    0.000
  Subject                      29   43287   1492.7     9.94    0.000
Error                         683  102586    150.2
```

Tukey's Post-hoc Analysis

Weight (W)

```
30     360  48.6982  A
10     360  41.5066         B
```

Carrying Method (C)

```
Lateral     180  58.3679  A
Frontal     180  42.8000      B
Posterior   180  41.0647      B  C
Bilateral   180  38.1772         C
```

W x C

```
Lateral 30     90  69.9364  A
Lateral 10     90  46.7993     B
Frontal 30     90  43.8146     B  C
Posterior 30   90  41.8057     B  C  D
Frontal 10     90  41.7853     B  C  D
Posterior 10   90  40.3237        C  D
Bilateral 30   90  39.2363        C  D
Bilateral 10   90  37.1182           D
```

XCoM deviation in the M/L direction during Single Support phases (mm)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	10.89	3.23	(0.87, 20.91)	3.37	0.021
F30 - Baseline	13.78	3.23	(3.75, 23.80)	4.27	0.001
L10 - Baseline	17.07	3.23	(7.05, 27.10)	5.29	0.000
L30 - Baseline	37.42	3.23	(27.40, 47.44)	11.59	0.000
B10 - Baseline	5.36	3.23	(-4.66, 15.38)	1.66	0.771
B30 - Baseline	6.95	3.23	(-3.08, 16.97)	2.15	0.438
P10 - Baseline	12.51	3.23	(2.49, 22.53)	3.88	0.003
P30 - Baseline	12.39	3.23	(2.37, 22.41)	3.84	0.004

Analysis of Variance

```
Source                         DF  Adj SS   Adj MS  F-Value  P-Value
  Carrying Method               3   43398  14466.1    42.16    0.000
  Load (lbs)                    1    6865   6864.8    20.01    0.000
  Carrying Method*Load (lbs)    3   12257   4085.8    11.91    0.000
  Subject                      29  110170   3799.0    11.07    0.000
Error                         683  234352    343.1
Total                         719  407042
```

Tukey's Post-hoc Analysis

Weight (W)

```
30     360  103.181  A
10     360   97.005         B
```

Carrying Method (C)

```
Lateral     180  112.796  A
Posterior   180   97.998      B
Frontal     180   97.879      B
Bilateral   180   91.699         C
```

W x C	Lateral 30	90	122.970	A
	Lateral 10	90	102.621	B
	Frontal 30	90	99.324	B C
	Posterior 10	90	98.059	B C D
	Posterior 30	90	97.937	B C D
	Frontal 10	90	96.435	B C D
	Bilateral 30	90	92.493	C D
	Bilateral 10	90	90.906	D

Cadence (Steps/ min)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	5.92	1.21	(2.16, 9.67)	4.89	0.000
F30 - Baseline	12.44	1.21	(8.69, 16.20)	10.29	0.000
L10 - Baseline	2.59	1.21	(-1.16, 6.35)	2.14	0.443
L30 - Baseline	7.27	1.21	(3.52, 11.03)	6.01	0.000
B10 - Baseline	2.45	1.21	(-1.30, 6.21)	2.03	0.525
B30 - Baseline	5.54	1.21	(1.78, 9.29)	4.58	0.000
P10 - Baseline	4.36	1.21	(0.61, 8.12)	3.61	0.009
P30 - Baseline	5.98	1.21	(2.23, 9.74)	4.95	0.000

Analysis of Variance

```
Source                          DF   Adj SS   Adj MS  F-Value  P-Value
  Carrying Method                3   2849.4   949.79    38.41    0.000
  Load (lbs)                     1   2848.6  2848.59   115.19    0.000
  Carrying Method*Load (lbs)     3    599.5   199.82     8.08    0.000
  Subject                       29  31878.0  1099.24    44.45    0.000
Error                          683  16890.1    24.73
Total                          719  55065.5
```

Tukey's Post-hoc Analysis

Weight (W)	30	360	112.717	A
	10	360	108.739	B
Carrying Method (C)	Frontal	180	114.088	A
	Posterior	180	110.082	B
	Lateral	180	109.840	B
	Bilateral	180	108.902	B

W x C

```
Frontal 30     90  117.351  A
Lateral 30     90  112.178     B
Posterior 30   90  110.893     B  C
Frontal 10     90  110.825     B  C
Bilateral 30   90  110.446     B  C
Posterior 10   90  109.270        C  D
Lateral 10     90  107.501           D
Bilateral 10   90  107.359           D
```

Walking Speed (m/s)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	-0.0007	0.0169	(-0.0532, 0.0518)	-0.04	1.000
F30 - Baseline	0.0229	0.0169	(-0.0296, 0.0754)	1.35	0.915
L10 - Baseline	-0.0044	0.0169	(-0.0570, 0.0481)	-0.26	1.000
L30 - Baseline	0.0029	0.0169	(-0.0496, 0.0555)	0.17	1.000
B10 - Baseline	0.0046	0.0169	(-0.0479, 0.0572)	0.27	1.000
B30 - Baseline	0.0100	0.0169	(-0.0425, 0.0625)	0.59	1.000
P10 - Baseline	0.0063	0.0169	(-0.0463, 0.0588)	0.37	1.000
P30 - Baseline	0.0133	0.0169	(-0.0392, 0.0658)	0.79	0.997

Analysis of Variance

```
Source                          DF   Adj SS    Adj MS  F-Value  P-Value
  Carrying Method                3  0.01930  0.006435     1.31    0.269
  Load (lbs)                     1  0.01232  0.012324     2.51    0.113
  Carrying Method*Load (lbs)     3  0.01334  0.004446     0.91    0.437
  Subject                       29  4.24987  0.146547    29.89    0.000
Error                          683  3.34869  0.004903
Total                          719  7.64352
```

In here, nothing was statistically significant.

Stride Length (m)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	-0.0226	0.0120	(-0.0597, 0.0145)	-1.89	0.623
F30 - Baseline	-0.0497	0.0120	(-0.0868, -0.0126)	-4.16	0.001
L10 - Baseline	-0.0035	0.0120	(-0.0406, 0.0336)	-0.29	1.000
L30 - Baseline	-0.0121	0.0120	(-0.0492, 0.0250)	-1.01	0.985
B10 - Baseline	0.0272	0.0120	(-0.0099, 0.0643)	2.27	0.358

B30 - Baseline	-0.0072	0.0120	(-0.0443, 0.0299)	-0.60	1.000
P10 - Baseline	0.0094	0.0120	(-0.0277, 0.0465)	0.79	0.997
P30 - Baseline	0.0104	0.0120	(-0.0267, 0.0475)	0.87	0.994

Analysis of Variance

```
Source                         DF   Adj SS    Adj MS  F-Value  P-Value
  Carrying Method               3  0.25543  0.085143    23.10    0.000
  Load (lbs)                    1  0.05368  0.053683    14.57    0.000
  Carrying Method*Load (lbs)    3  0.03604  0.012014     3.26    0.021
  Subject                      29  2.05790  0.070962    19.26    0.000
Error                         683  2.51704  0.003685
Total                         719  4.92009
```

Tukey's Post-hoc Analysis:

Weight (W)	`10     360  1.23075  A` `30     360  1.21348         B`

Carrying Method (C)	`Bilateral  180  1.23808  A`
	`Posterior  180  1.23804  A`
	`Lateral    180  1.22034      B`
	`Frontal    180  1.19200         C`

W x C	`Bilateral 10  90  1.25529  A`
	`Posterior 30  90  1.23855  A  B`
	`Posterior 10  90  1.23754  A  B`
	`Lateral 10    90  1.22462     B  C`
	`Bilateral 30  90  1.22088     B  C`
	`Lateral 30    90  1.21606     B  C`
	`Frontal 10    90  1.20556        C  D`
	`Frontal 30    90  1.17843           D`

Double Support (% of gait cycle)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	0.00134	0.00368	(-0.01010, 0.01278)	0.36	1.000
F30 - Baseline	0.01511	0.00368	(0.00367, 0.02655)	4.10	0.001
L10 - Baseline	-0.00356	0.00368	(-0.01500, 0.00788)	-0.97	0.989
L30 - Baseline	0.01351	0.00368	(0.00207, 0.02494)	3.67	0.008
B10 - Baseline	-0.00331	0.00368	(-0.01475, 0.00812)	-0.90	0.993
B30 - Baseline	0.01093	0.00368	(-0.00051, 0.02237)	2.97	0.074
P10 - Baseline	-0.00438	0.00368	(-0.01582, 0.00706)	-1.19	0.959
P30 - Baseline	0.01650	0.00368	(0.00506, 0.02794)	4.48	0.000

Analysis of Variance

```
Source                        DF    Adj SS    Adj MS  F-Value  P-Value
  Carrying Method              3  0.002277  0.000759     2.07    0.103
  Load (lbs)                   1  0.051571  0.051571   140.32    0.000
  Carrying Method*Load (lbs)   3  0.001272  0.000424     1.15    0.327
  Subject                     29  0.169691  0.005851    15.92    0.000
Error                        683  0.251026  0.000368
Total                        719  0.475838
```

Tukey's Post-hoc Analysis:

Weight (W)	30 360 0.225349 A 10 360 0.208423 B
Carrying Method (C)	Carrying methods is insignificant
W x C	Interaction is insignificant

Step Width (mm)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	-4.15	3.71	(-15.66, 7.36)	-1.12	0.971
F30 - Baseline	-3.75	3.71	(-15.26, 7.76)	-1.01	0.985
L10 - Baseline	-10.73	3.71	(-22.24, 0.79)	-2.89	0.091
L30 - Baseline	-19.57	3.71	(-31.08, -8.06)	-5.28	0.000
B10 - Baseline	-21.06	3.71	(-32.57, -9.55)	-5.68	0.000
B30 - Baseline	-12.37	3.71	(-23.88, -0.86)	-3.33	0.024
P10 - Baseline	-0.78	3.71	(-12.29, 10.74)	-0.21	1.000
P30 - Baseline	-15.02	3.71	(-26.54, -3.51)	-4.05	0.002

Analysis of Variance

```
Source                        DF  Adj SS  Adj MS  F-Value  P-Value
  Carrying Method              3   20495  6831.7    16.06    0.000
  Load (lbs)                   1    2678  2677.7     6.29    0.012
  Carrying Method*Load (lbs)   3   15310  5103.4    12.00    0.000
  Subject                     29  116178  4006.1     9.42    0.000
```

```
Error                         683  290573   425.4
Total                         719  445234
```

Tukey's Post-hoc Analysis

Weight (W)	10	360	199.489	A
	30	360	195.632	B
Carrying Method (C)	Frontal	180	204.359	A
	Posterior	180	201.126	A
	Lateral	180	193.161	B
	Bilateral	180	191.596	B
W x C	Posterior 10	90	208.965	A
	Frontal 30	90	204.561	A B
	Frontal 10	90	204.157	A B
	Lateral 10	90	197.584	B C
	Bilateral 30	90	195.941	B C D
	Posterior 30	90	193.286	C D
	Lateral 30	90	188.739	C D
	Bilateral 10	90	187.251	D

Normalized A/P Shear Force (N/kg)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	0.582	0.156	(0.097, 1.068)	3.73	0.006
F30 - Baseline	1.464	0.156	(0.979, 1.949)	9.36	0.000
L10 - Baseline	0.486	0.156	(0.000, 0.971)	3.11	0.049
L30 - Baseline	1.248	0.156	(0.763, 1.733)	7.98	0.000
B10 - Baseline	0.030	0.156	(-0.455, 0.515)	0.19	1.000
B30 - Baseline	1.282	0.156	(0.797, 1.768)	8.20	0.000
P10 - Baseline	0.390	0.156	(-0.095, 0.876)	2.50	0.233
P30 - Baseline	1.002	0.156	(0.517, 1.488)	6.41	0.000

Analysis of Variance

```
Source                         DF   Adj SS   Adj MS  F-Value  P-Value
  Carrying Method               3   58.093  19.3644    30.77    0.000
  Load (lbs)                    1   63.642  63.6415   101.12    0.000
  Carrying Method*Load (lbs)    3    8.155   2.7184     4.32    0.005
  Subject                      29  269.157   9.2813    14.75    0.000
Error                         683  429.860   0.6294
Total                         719  828.907
```

Tukey’s Post-hoc Analysis

Weight (W)

```
30     360  5.86482  A
10     360  5.27021          B
```

Carrying Method (C)

```
Frontal    180  5.88452  A
Lateral    180  5.75961  A
Posterior  180  5.47995      B
Bilateral  180  5.14599          C
```

W x C

```
Frontal 30    90  6.31594  A
Lateral 30    90  6.12622  A
Posterior 30  90  5.64534      B
Frontal 10    90  5.45309      B
Lateral 10    90  5.39299      B
Bilateral 30  90  5.37178      B
Posterior 10  90  5.31455      B
Bilateral 10  90  4.92020          C
```

Normalized Compression Force (N/kg)

Tukey Simultaneous Tests for Differences of Means compared to the baseline

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
F10 - Baseline	1.239	0.319	(0.249, 2.229)	3.89	0.003
F30 - Baseline	2.773	0.319	(1.783, 3.763)	8.70	0.000
L10 - Baseline	1.157	0.319	(0.167, 2.147)	3.63	0.009
L30 - Baseline	2.898	0.319	(1.908, 3.888)	9.09	0.000
B10 - Baseline	0.984	0.319	(-0.006, 1.974)	3.08	0.053
B30 - Baseline	2.434	0.319	(1.444, 3.424)	7.63	0.000
P10 - Baseline	1.275	0.319	(0.285, 2.265)	4.00	0.002
P30 - Baseline	2.815	0.319	(1.825, 3.805)	8.83	0.000

Analysis of Variance

```
Source                          DF   Adj SS   Adj MS  F-Value  P-Value
  Carrying Method                3    13.74    4.581     4.50    0.004
  Load (lbs)                     1   441.67  441.667   433.54    0.000
  Carrying Method*Load (lbs)     3     2.07    0.688     0.68    0.567
  Subject                       29  2860.32   98.632    96.82    0.000
Error                          683   695.81    1.019
Total                          719  4013.60
```

Tukey's Post-hoc Analysis

Weight (W)

```
30     360  14.6463  A
10     360  13.0799        B
```

Carrying Method (C)

```
Carrying
Method        N     Mean  Grouping
Posterior  180  13.9614  A
Lateral    180  13.9437  A
Frontal    180  13.9223  A
Bilateral  180  13.6250         B
```

W x C

```
   Interaction is insignificant
```

Trunk Extension/ Flexion

Analysis of Variance

```
Source                        DF   Adj SS   Adj MS  F-Value  P-Value
  Carrying Method              3   6643.4  2214.45   403.02    0.000
  Load (lbs)                   1    212.5   212.50    38.67    0.000
  Carrying Method*Load (lbs)   3    518.4   172.82    31.45    0.000
  Subject                     29   3235.4   111.57    20.30    0.000
Error                        683   3752.8     5.49
Total                        719  14362.5
```

Tukey's Post-hoc Analysis

Weight (W)

```
Posterior  180   5.06009  A
Lateral    180   3.37993     B
Bilateral  180   2.51409        C
Frontal    180  -3.03752           D
```

Carrying Method (C)

```
30     360  2.52241  A
10     360  1.43588        B
```

W x C

```
Posterior 30  90   6.58695  A
Lateral 30    90   4.61900     B
Posterior 10  90   3.53322        C
Bilateral 10  90   2.71448        C  D
Bilateral 30  90   2.31371           D
Lateral 10    90   2.14087           D
Frontal 10    90  -2.64503              E
Frontal 30    90  -3.43002              E
```

Trunk Lateral Bending

Analysis of Variance

```
Source                          DF   Adj SS   Adj MS  F-Value  P-Value

  Carrying Method                3   794.64  264.880    99.57    0.000
  Load (lbs)                     1     3.33    3.329     1.25    0.264
  Carrying Method*Load (lbs)     3    58.46   19.487     7.33    0.000
  Subject                       29  1631.15   56.247    21.14    0.000
Error                          683  1816.99    2.660
Total                          719  4304.57
```

Tukey's Post-hoc Analysis:

Weight (W)

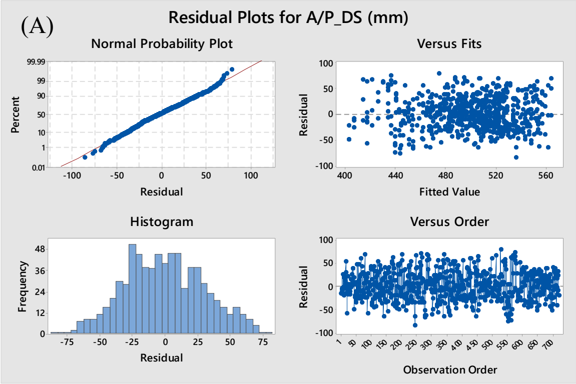
```
Weight is insignificant
```

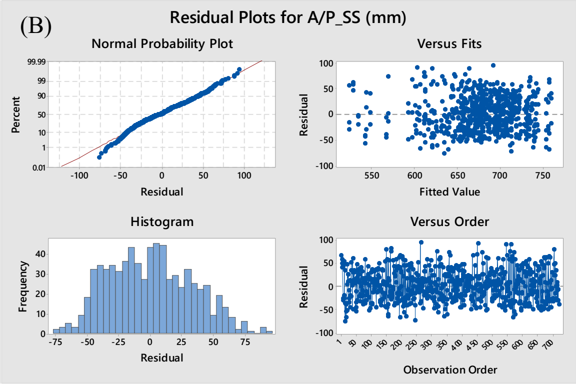
Carrying Method (C)

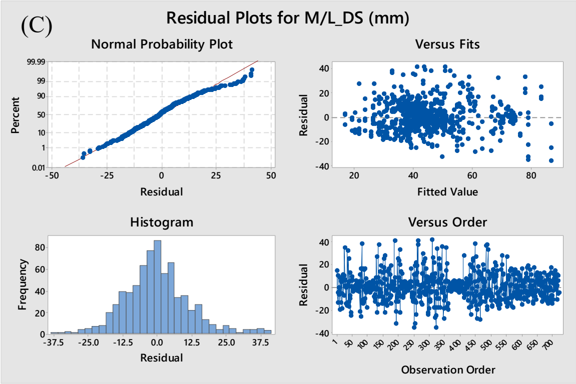
```
Frontal    180   1.14225  A
Posterior  180   0.68009      B
Bilateral  180   0.52207      B
Lateral    180  -1.58691         C
```

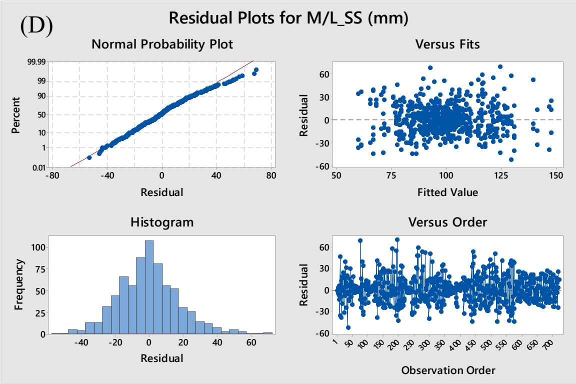
W x C

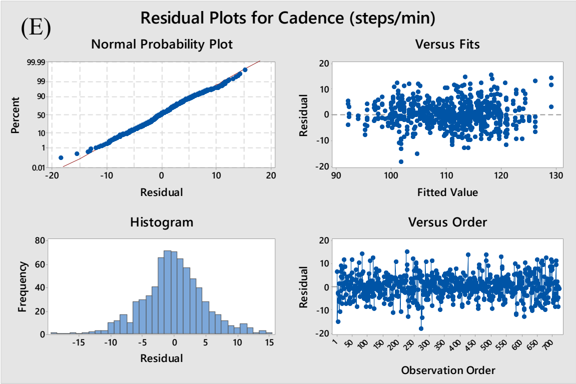
```
Frontal 30    90   1.27950  A
Frontal 10    90   1.00500  A  B
Posterior 30  90   0.82228  A  B
Posterior 10  90   0.53790     B
Bilateral 30  90   0.52222     B
Bilateral 10  90   0.52192     B
Lateral 10    90  -1.03535        C
Lateral 30    90  -2.13847           D
```

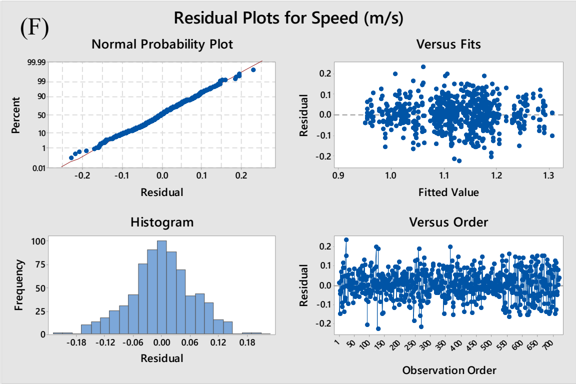

(A)
Residual Plots for A/P_DS (mm)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-100
-50
0
50
100
Residual
Versus Fits
Residual
100
50
0
-50
-100
400
440
480
520
560
Fitted Value
Histogram
Frequency
48
36
24
12
0
-75
-50
-25
0
25
50
75
Residual
Versus Order
Residual
100
50
0
-50
-100
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order

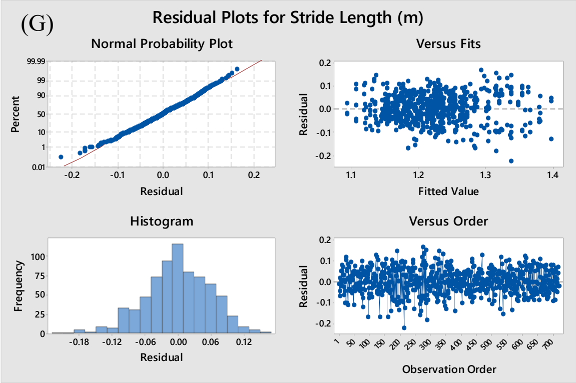

(B)
Residual Plots for A/P_SS (mm)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-100
-50
0
50
100
Residual
Versus Fits
Residual
100
50
0
-50
-100
550
600
650
700
750
Fitted Value
Histogram
Frequency
40
30
20
10
0
-75
-50
-25
0
25
50
75
Residual
Versus Order
Residual
100
50
0
-50
-100
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order

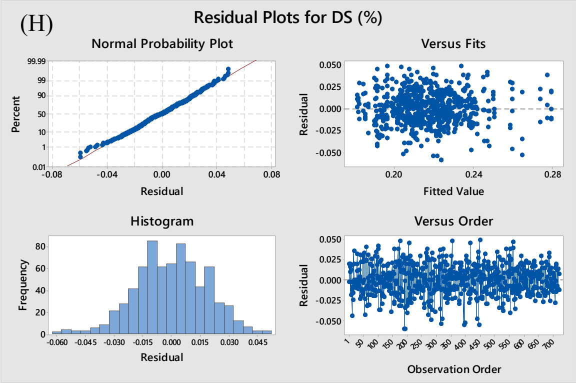

(C)
Residual Plots for M/L_DS (mm)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-50
-25
0
25
50
Residual
Versus Fits
Residual
40
20
0
-20
-40
20
40
60
80
Fitted Value
Histogram
Frequency
80
60
40
20
0
-37.5
-25.0
-12.5
0.0
12.5
25.0
37.5
Residual
Versus Order
Residual
40
20
0
-20
-40
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order


(D)
Residual Plots for M/L_SS (mm)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-80
-40
0
40
80
Residual
Versus Fits
Residual
60
30
0
-30
-60
50
75
100
125
150
Fitted Value
Histogram
Frequency
100
75
50
25
0
-40
-20
0
20
40
60
Residual
Versus Order
Residual
60
30
0
-30
-60
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order


(E)
Residual Plots for Cadence (steps/min)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-20
-10
0
10
20
Residual
Versus Fits
Residual
20
10
0
-10
-20
90
100
110
120
130
Fitted Value
Histogram
Frequency
80
60
40
20
0
-15
-10
-5
0
5
10
15
Residual
Versus Order
Residual
20
10
0
-10
-20
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order


(F)
Residual Plots for Speed (m/s)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-0.2
-0.1
0.0
0.1
0.2
Residual
Versus Fits
Residual
0.2
0.1
0.0
-0.1
-0.2
0.9
1.0
1.1
1.2
1.3
Fitted Value
Histogram
Frequency
100
75
50
25
0
-0.18
-0.12
-0.06
0.00
0.06
0.12
0.18
Residual
Versus Order
Residual
0.2
0.1
0.0
-0.1
-0.2
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order


(G)
Residual Plots for Stride Length (m)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-0.2
-0.1
0.0
0.1
0.2
Residual
Versus Fits
Residual
0.2
0.1
0.0
-0.1
-0.2
1.1
1.2
1.3
1.4
Fitted Value
Histogram
Frequency
100
75
50
25
0
-0.18
-0.12
-0.06
0.00
0.06
0.12
Residual
Versus Order
Residual
0.2
0.1
0.0
-0.1
-0.2
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order


(H)
Residual Plots for DS (%)
Normal Probability Plot
Percent
99.99
99
90
50
10
1
0.01
-0.08
-0.04
0.00
0.04
0.08
Residual
Versus Fits
Residual
0.050
0.025
0.000
-0.025
-0.050
0.20
0.24
0.28
Fitted Value
Histogram
Frequency
80
60
40
20
0
-0.060
-0.045
-0.030
-0.015
0.000
0.015
0.030
0.045
Residual
Versus Order
Residual
0.050
0.025
0.000
-0.025
-0.050
1 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Observation Order

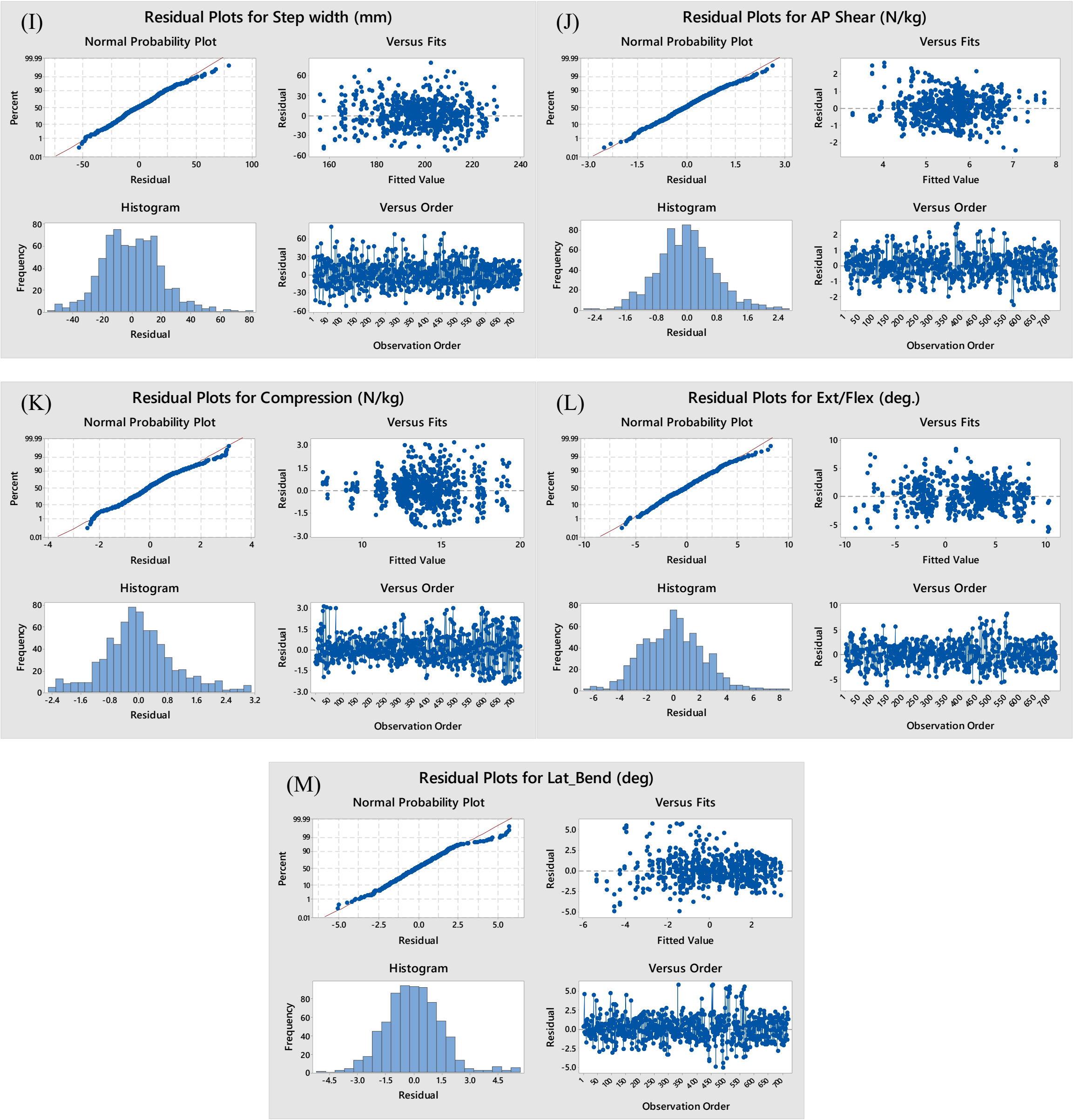


Figure A – 3. Normal probability plot, residuals vs. fits, histogram, and residuals vs. observation for (A) A/P Deviation of the XCoM during DS (B) A/P Deviation of the XCoM during SS (C) M/L Deviation of the XCoM during DS (D) M/L Deviation of the XCoM during SS (E) Cadence (F) Walking speed (G) Stride length (H) DS duration (I) Step width (J) Normalized compression force (K) Normalized shear force (L) Trunk extension/ flexion (M) Trunk lateral bending.

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

TITLE: Quantitative analysis of human biomechanics during occupational activities

INVESTIGATORS: Shihab Asfour, PhD,
Francesco Travascio, PhD

LOCATION:
University of Miami
Biomechanics Research Laboratory
1251 Memorial Drive
McArthur Building, Room 155 (past sliding doors)
Coral Gables, FL 33146

SUMMARY:

You are being asked to be in the study because musculoskeletal activity during occupational activities will be analyzed. Should you decide to participate in this analysis after your questions have been answered, you will be asked to sign and date this consent and authorization form. There are several things you should know about your participation:

1. You are being asked to participate in a motion analysis study on occupational activities.
2. Your decision to be in this research study is voluntary.
3. Your choice to participate or not to participate will not influence your relationship with the University of Miami.
4. If you decide to be in this study and then change your mind, you can leave the study at any time by contacting the primary investigator, Dr. Shihab Asfour at 305-607-7676.
5. There are no known side effects for this study.
6. This is not a treatment study.
7. The entire process will not take more than 1 year.
8. If you agree to be in this research study, all data collected during the experiment will belong to the Biomechanics Research Lab.
9. We do not anticipate any sort of injuries as a result of this study. However, if you are injured in this study, your medical insurance may be billed for any treatment you need. Your insurance would then have access to the research records and would know that you were in the study.

More detailed information about this study is in this consent form. Please read carefully and ask any questions you may have about this study.

PURPOSE:

The objective of this study is to quantify the musculoskeletal performance, in terms of muscular activity and joints kinematics during occupational activities in Transportation, Warehousing & Utilities (TWU) sectors (i.e., walking, stair climbing, lifting, carrying objects, etc.). More information regarding the experiment is provided in the “procedures” section.

NUMBER OF STUDY PARTICIPANTS:

About 200 males and 200 female subjects will participate in the study at the University of Miami Biomechanics Research Laboratory.

PROCEDURES:

The following information about you will be collected prior to the analysis:

- Subject age
- Body weight
- Body height
- Shoulder offset
- Elbow width
- Wrist width
- Hand thickness
- Leg length
- Knee width
- Ankle width
- Individual perception of workload demand after performing an experimental task
- Waist circumference
- Waist-to-hip ratio
- Skinfold Thickness

For your safety, all the experimental setups will follow ergonomic guidelines prepared by NIOSH (National Institute for Occupational Safety and Health). Should you feel tired at any point during the experiments, you will be provided a chair to rest in-between trials. An assistant will be present at all times during the experiments.

In this study you will be asked to do four different occupational activities, including:

- **Walking -** You will be asked to walk on a treadmill at different speeds (max. 4mph) and inclinations (from 0 to 10%). For your safety, your heart rate will be recorded during the experiment and your target heart value will be calculated according to Centers for Disease and Control Prevention's formula. When your heart rate exceeds your target heart value, the experiment will be stopped.

- **Lifting -** You will be asked to lift boxes in different experimental scenarios. More specifically, tasks will include: lifting boxes from floor to table height and from table height to shoulder height. In order to guarantee your safety, the amounts of weights lifted during experiments will be determined using NIOSH lifting equation. The maximum weight that you will be asked to lift will be 35lbs.

- **Load Carrying/ Moving -** You will be asked to carry boxes while walking on a treadmill. Boxes will be carried symmetrically ("0" angle from the front of your body) and asymmetrically (non-zero angle from the front of your body). In order to guarantee your safety, the amounts of weights carried/moved during experiments will be determined using NIOSH lifting equation.

- **Stair Climbing-** In this experiment, you will ascend and descend an FDA (U.S Food and Drug Administration) approved four-step staircase at your comfort speed.

RISKS AND DISCOMFORTS:

This study involves no more than minimal risk to participants. There are low risks associated with walking, stair climbing, lifting and load-carriage. These risks are similar to everyday activities. Experiments will be performed with a motion capture system which requires the application of skin-mounted markers on subjects. In order to prevent skin irritation caused by the chemical of the body marker tape, stretchable Velcro bands will be used instead of two-sided tapes. An assistant will be present at all times during the experiment. Should you feel tired at any point during the experiments, you will be provided enough rest time between trials.

BENEFITS:

You will not personally benefit from participating to this research study.

ALTERNATIVES:

You have the alternative not to participate to this study. You can decide to stop participating to this study at any time. Not participating to this study will not affect your relationship with the University of Miami.

COSTS:

There are no costs associated with your participation to the study.

PAYMENT FOR STUDY:

You will not be paid for participating to this study.

COMPENSATION FOR STUDY-RELATED INJURY:

Although risks are unlikely to happen, if injury should occur, treatment will in most cases be available. If you have insurance, your insurance company may or may not pay for these costs. If you do not have insurance, or if your insurance company refuses to pay, you will be expected to pay. Funds to compensate for pain, expenses, lost wages, and other damages cause by injury are not available.

VOLUNTARY PARTICIPATION/WITHDRAWAL FROM STUDY:

Your participation in this study is voluntary. You may refuse to participate, or withdraw from the study at any time, without penalty or loss of benefits to which you are otherwise entitled. You must tell the study staff if you wish to stop taking part to the study.

CONFIDENTIALITY:

By signing this consent, you authorize the Investigator(s) and his/her/their staff to access records associated to this experiment and associated information as may be necessary for purposes of this study. Your records and results will not be identified as pertaining to you in any publication without your expressed permission. The Investigators and their collaborators, and staff will consider your records confidential to the extent permitted by law. The Department of Health and Human Services (DHHS) and your health care providers, including authorized University or Hospital staff not involved in the study may review these research records. Your records may also be reviewed for audit purposes by authorized University of Miami employees or other agents who will be bound by the same provisions of confidentiality.

WHOM TO CONTACT:

If there are any questions about this research study, please contact Dr. Asfour at 305-607-7676.

If you have any questions relating to your rights as a research subject, please contact **the University of Miami's HUMAN SUBJECTS RESEARCH OFFICE (HSRO)**, at **305-243-3195**.

AGREEMENT OF DECISION TO PARTICIPATE:

You will receive a copy of this signed informed consent form.

I have read this consent, which is printed in English (a language which I read and understand). This study has been explained to my satisfaction and all of my questions relating to the study procedures, risks, and discomforts have been answered. If I have any further questions regarding this study, or in the event of a study-related injury, I should contact the appropriate person named above. Based on this information, I voluntarily agree to give permission (consent) for me to take part in this study.

______________________________ ______________

Signature of Participant Date

____

Printed Name of Participant

______________________________ ______________

Signature of Investigator Date

____

Printed Name of Investigator

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