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Effects of Load and Gradient on Musculoskeletal Loading During Dynamic Two-Wheeled Cart Pushing and Pulling

Yun Sun
West Virginia University

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Effects of Load and Gradient on Musculoskeletal Loading During Dynamic Two-Wheeled Cart Pushing and Pulling

Yun Sun

Dissertation submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy
in
Occupational Safety and Health

Ashish D. Nimbarte, Ph.D., Chair
Majid Jaraiedi, Ph.D.
Michael J. Klishis, Ph.D.
Avinash Unnikrishnan, Ph.D.
Hongwei Hsiao, Ph.D.

Department of Industrial and Management Systems Engineering

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Biomechanical Modeling; Inclined Walkway; Direction of Force Application

ABSTRACT

Effects of Load and Gradient on Musculoskeletal Loading During Dynamic Two-Wheeled Cart Pushing and Pulling

Yun Sun

Pushing and pulling of carts are found to be associated with low back pain and shoulder complaints. It is currently unclear as to how the dynamic pushing and pulling tasks performed under different task conditions (e.g. weight, walkway gradient, direction of force application) affect the musculoskeletal loading of low back and shoulder joints. Therefore, the objective in this study was to evaluate dynamic pushing and pulling tasks to quantify their effects on the 3D musculoskeletal loading of low back and shoulder joints. Twelve male participants performed cart pushing pulling tasks along a 5° and 10° ramp by carrying loads of 20, 30, and 40 kg, respectively. An eight-camera optical motion analysis system configured with two force plates was used for kinematic and kinetic data collection. The experimental data was modeled using Anybody musculoskeletal modeling system. A biomechanical model consisting of a two wheeled cart and a full-body human model (34 bones and over 750 muscle fascicles) was formulated in the AnyBody modeling system. The model was validated by comparing the predicted reaction forces on the cart wheels with the actual forces recorded experimentally using ground reaction force platforms. A high correlation between the actual and predicted data (average = 0.919) was observed. The results of this study show that as the cart weight increased, so did the low back and shoulder joint loads. A walkway gradient of 10° on average produced larger low back and shoulder joint forces than a gradient of 5°. Uphill pushing caused higher mechanical load on the low back and shoulder joints than the downhill pulling. The magnitude of peak lateral shear forces at the L5S1 joint was negligible (< 150 N). The largest peak compression force observed in this study (3222 N) was below the recommended NIOSH limit of 3400 N. The peak anterior-posterior shear forces during uphill pushing at 30 kg and 40 kg weight conditions on a gradient of 10° were 553 N and 806 N, respectively. These values exceed the tolerance limit of 500 N, suggesting that the anterior-posterior shear loading at the L5S1 joint should be considered when assessing the risk of musculoskeletal disorders due to pushing and pulling activities.

For the shoulder joints, the peak forces at the sternoclavicular joint were small (< 220 N) in all situations. At the glenohumeral joint, the peak distraction, compression and anterior-posterior shear forces were 1357 N, 858 N, and 618 N, respectively, during uphill pushing at 40 kg weight condition on a gradient of 10°. Under the same condition, the corresponding peak forces acting at the acromioclavicular joint were 910 N, 1078 N, and 727 N. In the existing literature, the focus has always been on the glenohumeral joint and loading of the sternoclavicular and acromioclavicular joints was not evaluated. The results of this research show that the peak forces acted at the acromioclavicular joint are comparable to those at the glenohumeral joint, further suggesting that the loading on the acromioclavicular joint should be considered, in addition to the glenohumeral joint, while evaluating risk of musculoskeletal disorders due to pushing and pulling activities.

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CHAPTER 1: INTRODUCTION

Work-related musculoskeletal disorders (MSD) are among the most costly health problems facing society today (National Research Council and Institute of Medicine, 2001). In the United States, MSD impose a substantial economic burden in terms of worker compensation costs, lost wages, and decreased productivity. Conservative cost estimates vary, but a reasonable number is between \$45 and \$54 billion annually (Dunning, et al., 2010). According to the Bureau of Labor Statistics (2010), MSD among the occupational groups such as laborers and material movers, heavy and tractor-trailer truck drivers, and delivery service truck drivers, whose routine work demands manual material handling (MMH) tasks, constitute 12 % of all MSD cases (144,910 out of 1,238,490 cases) requiring days away from work. The body parts that are most affected by MMH exertions include neck, upper extremities, and low back. Although neck and shoulder MSD are not as prominent as low back, these disorders contribute significantly to morbidity among various occupational groups and also put a substantial burden in terms of health and economics (Nonnenmann, et al., 2008; Hess, et al., 2010; Holmström, Lindell, & Moritz, 1992; Grooten, et al., 2004; Cassou, et al., 2002).

Manual material handling (MMH) tasks commonly performed at the workplaces primarily are comprised of activities such as lifting/lowering, pushing/pulling, and carrying loads (Snook, 1978; Smith, Woldstad, & Patterson, 2009). Traditionally, most of the exertions at workplaces that were linked with the physical risk factors such as high force and repetitive exertions were primarily during the lifting and lowering tasks. However, the workplace and the nature of the work are changing rapidly. Recently, most manufacturing is done offshore. With the introduction of e-commerce, a vast increase in distribution center jobs has also occurred where order picking with the use of cart pushing/pulling is becoming a common task for many workers. Collectively, these trends indicate that the nature of physical exposure is rapidly evolving to a highly repetitive environment where the repetition may involve different vectors of force application (Marras, et al., 2009). It has been estimated that nearly half of MMH tasks common at workplaces demand pushing and pulling exertions (Lee & Granata, 2006). In addition to

manufacturing workers, other occupations that demand pushing and pulling types of exertions on a daily basis include health care (Waters, Nelson, & Proctor, 2007; Seto, et al., 2006; Das & Wimpee, 2002), fire fighting (Gledhill & Jamnik, 1992), flight and rail catering (Glitsch, et al., 2007; Schaub, et al., 2007; Jäger, et al., 2007), postal distribution (Hoozemans, et al., 2007; Hoozemans, et al., 2004; van der Beek, et al., 2000), refuse collection (Schibye, Søgaaard, et al., 2001; Frings-Dresen, Kemper, Stassen, Markslag, et al., 1995; Frings-Dresen, Kemper, Stassen, Crolla, et al., 1995), construction (Søgaaard, et al., 2001) and garden raking (Kumar, 1995), retail, storage, and warehousing (Kumar, Narayan, & Bacchus, 1995).

Pushing and pulling tasks are characterized by the force exertions with the direction of the resultant force being horizontal. In pushing, the force is directed away from the body, and in pulling, the force is directed toward the body. According to Chaffin (1987), the risk of health complaints induced by pushing and pulling can arise from two types of hazards. Firstly, the musculoskeletal system can become physically over-exerted. Secondly, pushing and pulling is accompanied by an increased risk of accidents due to slipping or tripping, which can cause injuries to the musculoskeletal system. Among the prior type, an association between the work-related pushing/pulling exertions and complaints of low back pain is reported in a number of studies (Hoozemans, et al., 1998; van der Beek, et al., 1993; Ozguler, et al., 2000; Klein, Jensen, & Sanderson, 1984; Harber, et al., 1987; Garg & Moore, 1992; Fuortes, et al., 1994; Frymoyer, et al., 1980; Damkot, et al., 1984). Pushing and pulling types of exertion are also implicated as a risk factor for the proliferation of MSD of the shoulder region and other upper extremities (Hoozemans, et al., 1998; van der Beek, et al., 1993; Smedley, et al., 2003; Hoozemans, et al., 2002a, 2002b). Given recent advances in research and the changing work environment, the National Institute for Occupational Safety and Health (NIOSH) addressed in its national occupational research agenda (NORA) that “...Efforts to quantitatively link epidemiological, biomechanical loading, soft tissue tolerance, and psychosocial factors studies should be pursued to establish a better understanding of the pathways of injury and resultant preventive strategies.” (Marras, et al., 2009)

To gain insight into the causal relationship between low back and shoulder MSD and pushing/pulling exertions, work-related pushing and pulling exertions were evaluated in a number of experimental studies. Early pushing/pulling studies focused predominantly on evaluation of static exertions (Chaffin, Andres, & Garg, 1983; Kroemer, 1974; Ayoub & Mcdaniel, 1974). The recent studies that evaluated dynamic exertions primarily focused on investigating changes in the magnitude of hand forces corresponding to different pushing/pulling techniques (Todd, 2005; Resnick & Chaffin, 1995; Bennett, et al., 2008) and the effect of pushing/pulling exertions on various physiological parameters, such as heart rate and oxygen uptake, etc. (van der Beek, et al., 2000; Frings-Dresen, Kemper, Stassen, Markslag, et al., 1995; Frings-Dresen, Kemper, Stassen, Crolla, et al., 1995; van der Beek & Frings-Dresen, 1995). Only a few studies looked at the effect of dynamic pushing/pulling exertions on the musculoskeletal loading (Jäger, et al., 2007; Hoozemans, et al., 2004; Schibye, Søgaaard, et al., 2001; Laursen & Schibye, 2002). Within industrial settings, dynamic pushing and pulling exertions performed on flat or inclined walkways are highly prevalent. Dynamic movement imposes different demands on the musculoskeletal system and several biomechanical models and epidemiologic studies suggest that the dynamic work is associated with a higher risk of injury compared to static work (Allread, Marras, & Burr, 2000; Marras, et al., 1993).

Currently, it is not clearly understood as to how the dynamic pushing/pulling exertions performed under different task conditions (e.g. weight, walkway gradient, direction of force application) affect the musculoskeletal loading of low back and shoulder joints. Quantification of three-dimensional (3D) loads experienced by certain joints (e.g., the spine and shoulder joints) is essential to better understand the pathways of injury and to develop adequate intervention strategies. Therefore, the purpose of the present study was to evaluate dynamic pushing and pulling tasks performed under different workplace conditions to quantify their effects on the musculoskeletal loading of major low back and shoulder joints. The tasks evaluated in this study were pushing a cart with loads of 20, 30, and 40 kg on a level walkway and while going uphill along 5° and 10° ramps. In addition, pulling tasks while going downhill were also evaluated. An eight-camera optical motion system configured with two ground reaction force plates was used

for data collection. The experimental data were exported in the C3D format, which were then used for running a full-body musculoskeletal model to compute the biomechanical loading in terms of joint reaction forces in three anatomical directions acting at the L5S1 joint of low back and three shoulder joints (sternoclavicular, acromioclavicular and glenohumeral joints) in the shoulder complex.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Manual material handling (MMH) tasks consist of a wide range of activities including lifting, lowering, carrying, pushing, and pulling (Snook, 1978; Smith, et al., 2009) and have long been a focus for a diverse range of disciplines as a result of the large economic and human cost of injuries incurred by workers involved in MMH (Mital, Nicholson, & Ayoub, 1997). Workplace pushing and pulling exertions involve the use of trolleys, pallet jacks, and other wheeled devices that allow for the movement of a larger quantity of goods (van der Beek, et al., 1999). Pushing/pulling tasks performed using a host of manual transport aids may seem relatively safe in terms of musculoskeletal loading, however the literature indicates that with pushing/pulling activities, the nature of risk is changed rather than eliminated (Resnick & Chaffin, 1995). Work-related pushing/pulling activities are generally identified amongst the risk factors associated with musculoskeletal disorders such as low back pain, shoulder stiffness, and upper extremity complaints (Hoozemans, et al., 1998).

In this chapter, studies evaluating pushing and pulling tasks are reviewed. The studies are classified into five sections: (1) fundamental concepts of work-related pushing and pulling exertions; (2) relationship between work-related musculoskeletal disorders and pushing/pulling exertions; (3) static and dynamic pushing/pulling exertions; (4) factors affecting pushing/pulling tasks with a focus on the effect of load weight, walkway gradient, and direction of exerted forces; and (5) musculoskeletal models evaluating pushing/pulling exertions.

2.2 Work-Related Pushing and Pulling Exertions

In general, pushing and pulling could be defined as the exertion of a force using the hand where direction of the resultant force is horizontal (Hoozemans, et al., 1998). However, depending on the location of the hands, it is necessary to note that an exertion of force is not always directed horizontally, for instance, in pulling a cord to start a lawn

mower engine, the force is directed vertically (Garg, Funke, & Janisch, 1988). In the present study, “uphill pushing” and “downhill pulling” exertions along an inclined walkway with the direction of the resultant force being horizontal were considered, where force is directed away from the body during pushing and toward the body during pulling.

2.3 Musculoskeletal Disorders: Pushing and Pulling

Numerous studies have reported that the risk of health complaints induced by pushing and pulling can arise from two types of hazards (Hoozemans, et al., 1998). First, the musculoskeletal system can become physically over-exerted due to excessive, too long, or too frequent force applications (Glitsch, et al., 2007). Second, pushing and pulling are accompanied by additional dangers from slipping and tripping when maneuvering hand-propelled transport vehicles, which can cause acute injuries to the musculoskeletal system (Glitsch, et al., 2007; Grieve, 1983). In the present study, the focus was on understanding how the musculoskeletal loading was altered with the changes in the load weight transferred and other workplace characteristics so that the pathomechanism of musculoskeletal injuries caused by the physical overexertion could be understood.

Many authors have suggested pushing and pulling as an occupational risk factor for low back pain (Hoozemans, et al., 1998; van der Beek, et al., 1993; Ozguler, et al., 2000; Klein, et al., 1984; Harber, et al., 1987; Garg & Moore, 1992; Fuortes, et al., 1994; Frymoyer, et al., 1980; Damkot, et al., 1984; NIOSH, 1997, 1981). NIOSH (1997) reported that 52% of the injuries leading to the back pain were associated with pushing and pulling. Garg and Moore (1992) found that work-related pushing and pulling activities account for 9-18% of all back strains and sprains. Harber et al. (1987) investigated the relationship between back pain and work factors among hospital nurses by using survey questionnaires. Carrying and pushing were combined in one factor and were significantly related to back pain. In another questionnaire study performed among Dutch workers, it was found that workers who frequently pushed or pulled objects at work reported low back pain more often than those who did not (Hoozemans, et al., 1998).

In addition to the low back MSD, several studies have also claimed that pushing and pulling exertions are associated with shoulder complaints (Hoozemans, et al., 1998; van der Beek, et al., 1993; Smedley, et al., 2003; Hoozemans, et al., 2002a, 2002b; Hughes, Silverstein, & Evanoff, 1997). Van der Beek et al. (1993) investigated the prevalence of musculoskeletal complaints in lorry drivers and found significantly a higher number of neck, shoulder and upper and lower extremity complaints in the lorry drivers who regularly pushed or pulled wheeled cages during the working day compared to those who only performed driving tasks. In an another study by Smedley et al. (2003), patient handling tasks that demand reaching, pushing, and pulling were identified as the physical risk factors for neck and shoulder MSD. Hughes et al. (1997) identified pushing and pulling tasks as a risk factor for shoulder MSD among the aluminum smelter workers. A dose-response relationship between the work-related pushing/pulling exertions and complaints of shoulder pain was also reported by Hoozemans et al. (2002a, 2002b).

The common work-related pathologies associated with the shoulder complex include: shoulder tendinitis, rotator cuff pain, and nonspecific shoulder pain. Repetitive loading of shoulder joints has been identified as one of the causal factors for these shoulder complex pain syndromes (NIOSH, 1997). The shoulder mechanism provides the upper limb with an extensive range of movement exceeding that of any other joint mechanism. The shoulder complex consists of three joints: sternoclavicular (SC), acromioclavicular (AC), and glenohumeral (GH) joints and the scapulothoracic gliding mechanism.

The SC joint, the only synovial articulation between the upper limb and the axial skeleton, has three degrees of freedom of movement. Because the distal end of the clavicle is attached to the AC joint, all movements of the clavicle are accompanied by movements of the scapula. Motions at the SC joint consist of: elevation/depression, protraction/retraction, and rotation (Reese, Bandy, & Yates, 2009). The AC joint is classified as a plane synovial joint and is formed by the articulation of the acromial end of the clavicle with the medial border of the acromion process of the scapula. The AC joint has been described as having three degrees of freedom of movement. These

movements are rotation, winging, and tilting, which occur during scapular motions of rotation, abduction/adduction, and elevation/depression, respectively (Reese, et al., 2009). The GH joint is a synovial ball-and-socket joint between the humeral head and the glenoid fossa of the scapula. The shallowness of the glenoid fossa and the disproportionate size and lack of congruency of the articular surfaces make the joint inherently unstable (Culham & Peat, 1993). This relative instability of the GH joint allows higher freedom of movement, permitting placement of the upper extremity in a wide variety of positions for function. The joint possesses three degrees of freedom, allowing the motions of flexion/extension, abduction/adduction, and medial/lateral rotation (Reese, et al., 2009). In addition to the three joints, a scapulothoracic and a subacromial joint are often included in anatomical descriptions of the shoulder complex. Together, these articulations provide the shoulder a wide range of mobility, together with elbow motion, allows positioning of the hand anywhere, which may cause overuse injuries for the shoulder complex.

2.4 Static and Dynamic Exertions

Pushing and pulling tasks common at workplaces may involve static and/or dynamic exertions, or a combination of both, with most dynamic efforts including a static component usually in the trunk and upper extremities (Garcin, et al., 1996). Static exertions most often involve supporting/controlling fixed objects or apparatus, resulting in the force exertion against a stationary target (Lee, et al., 1991). Conversely, dynamic exertions usually involve force exertion to transport loads, causing object displacement (Lee, et al., 1991).

Static pushing/pulling tasks have historically been at the core of scientific investigations that evaluated either maximum push/pull forces (Chaffin, et al., 1983; Kroemer, 1974; Ayoub & Mcdaniel, 1974) or low back muscle forces (Lee, et al., 1989), while pushing/pulling tasks in industry are predominantly dynamic (Todd, 2005; Bennett, et al., 2008). The differences between static and dynamic activities are mainly in terms of posture and force generation. For the same level of effort, body postures vary between the two, impacting on low back loading and implying that the ceiling parameters derived

statically may not be applicable to dynamic exertions. This was acknowledged by Resnick and Chaffin (1995) who stated that postures and forces change rapidly during dynamic pushing/pulling, and as such, optimal postures are not practicable for the duration of the task. Under low accelerations, peak pushing forces may approximate those of static efforts, suggesting that static estimations may be used to predict peak pushing forces at low accelerations, but when accelerations are high, dynamic standards will be necessary (Resnick & Chaffin, 1995). Some authors have advocated that static standards are inappropriate for evaluating dynamic exertions, considering that dynamic push/pull strength, being significantly lower than static ones (Kumar, et al., 1995; Mital, Kopardekar, & Motorwala, 1995).

Considering the prevalence of dynamic pushing/pulling exertions at workplaces (Lee, et al., 1991), a few studies have investigated dynamic pushing and pulling tasks, such as using two-wheeled waste containers (see Figure 2.1) (Schibye, Søgaaard, et al., 2001; Laursen & Schibye, 2002), collecting refuse in two-wheeled mini-containers or in large four-wheeled containers (Frings-Dresen, Kemper, Stassen, Markslag, et al., 1995; Frings-Dresen, Kemper, Stassen, Crolla, et al., 1995), wheeled cages used by postal workers (van der Beek, et al., 2000) or lorry drivers (van der Beek & Frings-Dresen, 1995), four-wheeled aircraft trolleys (see Figure 2.2) (Glitsch, et al., 2007; Jäger, et al., 2007), or standard four-wheeled carts as used in postal distribution centers (Hoozemans, et al., 2007; Hoozemans, et al., 2004). The primary outcome variables evaluated in these studies include hand forces, physiological parameters such as heart rate and oxygen uptake, two-dimensional (2D) loading of shoulder and lumbar spine, and three-dimensional (3D) loading of lumbar spine. Some of these studies will be revisited in the following sections.

Figure 2.1: Pushing and pulling of two-wheeled waste container (Laursen & Schibye, 2002)

Figure 2.2: Typical trolley handling on aircraft (Jäger, et al., 2007)

2.5 Factors Affecting Pushing and Pulling

Pushing/pulling tasks performed using manual transport vehicles are affected by a number of factors and a multifaceted interaction between them. These factors have been broadly categorized into design, environmental, task, and operator factors, as shown in Figure 2.3 (Jung, Haight, & Freivalds, 2005). The present study was aimed to investigate the effect of load weight, walkway gradient, and direction of force exertion on the musculoskeletal loading during dynamic pushing/pulling tasks performed using a two-wheeled hand truck. In terms of the factors most frequently considered important in a real industrial setting for pushing/pulling tasks, the effect of task factors (load weight and direction of force application) and environmental factors (walkway gradient) has not yet

been well studied in the literature. The literature related to the three aforementioned factors will be reviewed in the following sections.

Figure 2.3: Factors and usability of manual transport vehicle

2.5.1 Load weight

Load weight is one of the principal factors to be considered in the (re)design of push/pull tasks, because it is known to greatly affect force output and the loading of the musculoskeletal system (Resnick & Chaffin, 1995; Bennett, et al., 2008; Jung, et al., 2005). A survey of several industries by Mack et al. (1995) found a high variability in the load weight transferred using mechanical transfer aides by pushing/pulling actions. The load transferred per trip varied from 2 kg to 1500 kg on a hand pallet truck with distances varying from a few meters to hundreds of meters. Frings-Dresen et al. (1995) found that the weight of loads moved by refuse collectors, with a single individual, displaced average loads of 22 kg and 110 kg using mini and large containers, respectively . While a more recent study by St-Vincent et al. (2005) concluded that in a superstore, the total cumulative load moved using a pallet jack on a daily basis may be as high as 4400 kg. Despite the variability of the masses being moved, many authors have argued that regardless of vehicle type, load weight should be minimized to prevent excessive bodily stress (van der Beek, et al., 2000; Resnick & Chaffin, 1995), with the load's center of mass situated as low as possible (Kingma, et al., 2003).

In the study of Schibye et al. (2001), two loads (25 and 50 kg of waste) were used for the experiments, representing a filled and a heavily overfilled container, respectively. The container was pushed in front of and pulled behind the body by seven refuse collectors. A biomechanical analysis was made by using the Watbak system (University of Waterloo, Waterloo, Canada). The biomechanical calculations were based on a quasi-static 2D linked segment model. The results showed that during pushing and pulling of the two-wheeled container, the compression force at L4/L5 in all situations was rather small (605-1445 N) and never exceeded the value of 3400 N proposed as an acceptable limit by NIOSH (Waters, et al., 1993). The compression was smaller during pushing than during pulling. The compression was not affected by an increase in the amount of waste in the container. The shear forces at L4/L5 were generally small with the highest average value (200 N) obtained during pushing of the container. The external shoulder torque at the shoulder joint during pushing and pulling varied from -35 to 38 Nm. Flexion torques were positive during pushing and extension torques negative during pulling. Torque at the shoulder was larger during pushing or pulling of 50 kg compared to 25 kg.

In a study performed by Laursen and Schibye (2002), seven male waste collectors pushed and pulled a two-wheeled container on three different surfaces: flagstones, paving stones, and grass. The container was filled with 1, 2, or 4 newspaper bundles each weighing 12.5 kg. The biomechanical calculations were performed by software based on a 2D static linked segment model of the human body (Norman & McGill, 1993). The results showed that the lumbar spine compression force was below 1800 N and the shear force was below 200 N in all situations. The shoulder torque when pulling with one hand was up to 80 Nm. The container weight affected the magnitude of the push/pull forces and the load on the shoulders but not the load on the lumbar spine. The type of surface affected the magnitude of the push/pull forces during initial and sustained phases and affected the load on the shoulder in the sustained phase. However, it did not affect the compression in the lumbar spine.

With the use of a standard four-wheeled cart, Hoozemans et al. (2004) examined the effect of pushing and pulling three load weights, 85, 135, and 320 kg on the exerted forces and the mechanical load on the low back and shoulders. An upper body quasi-

dynamic 3D linked segment model was used to perform the biomechanical calculations. Results indicated that load weight affected each of the dependent variables (exerted forces, net moments, and compression and shear forces) significantly, i.e., an increase in load weight resulted in a significant increase of all dependent variables. For pushing or pulling at hip height, the predicted maximum compression force increased with 5 N for every kilogram that was added to the weight of the cart. With respect to the 320 kg cart used in this study, at hip height the maximum compression force at the low back was predicted to be 1600 N.

In the study of Bennett et al. (2008), in order to determine the impact of load on biomechanical responses during dynamic trolley pushing and pulling, participants pushed/pulled loads of 100, 200, and 300 kg on the level wooden walkway. When investigating load effect on hand forces, it was found that there existed a linear relationship between the two, with higher loads eliciting associated higher hand forces, particularly initial forces.

When investigating physical workload when handling trolleys on aircraft, Glitsch et al. (2007) used half-size and full-size trolleys in their study. The load mass of the trolleys ranged between 40 kg to 90 kg, therefore two intermediate weight conditions of 45 and 65 kg were evaluated in their study. It was found that the maximum hand forces during the pushing and pulling of trolleys showed a strong dependence on the weight of the trolley. On horizontal floors, the hand forces were in the range of 70-150 N, depending on trolley load. In the other part of the study (Jäger, et al., 2007) with the same laboratory set-up, 2500 N was chosen as the criterion for evaluating lumbar disc compression during trolley maneuvers. A spatial dynamic multi-segmental biomechanical model was used for quantifying the lumbar load during trolley handling. It illustrated that lumbar load clearly increased with increasing weight, indicating that the higher the load weight during pushing the trolleys, the higher the resultant lumbar-disc compression.

2.5.2 Walkway gradient

On one hand, a number of researchers have examined the biomechanics during normal gait on a level or inclined surface (Lay, Hass, & Gregor, 2006; Li, Chang, Lin, et

al., 2006; Li, Chang, Wei, et al., 2006; Prentice, et al., 2004; McIntosh, et al., 2006; Cham & Redfern, 2004; S. Redfern & DiPasquale, 1997; DiPasquale, 1997; Redfern, et al., 2001; Cham & Redfern, 2002a, 2002b). These studies focused on the prevention of slip/fall accidents, whereas, studies evaluating pushing and pulling types of exertion along ramps are sparse, despite the fact that the presence of variable inclined ramps in industry complicates the situation during pushing and pulling because of the task demands required to overcome the downward effect of gravity and the inertia of the object. In the study of Glisch et al. (2007), the floor gradients were used (0°, 2°, 5°, and 8°), and it was found that the maximum hand forces during the pushing and pulling of trolleys showed a strong dependence on the gradient of the floor. Depending on the trolley load, the forces were 70-150 N on average on horizontal floors; while on an 8° gradient, average maximum manual handling forces between 130 and 270 N were recorded, which in several cases proved to be excessively strenuous for women if the trolley was fully laden. Within the same experimental set-up, Jäger et al. (2007) found that during trolley pushing, lumbar load clearly increased with the increasing gradient. However, it was found that lumbar load did not increase with floor steepness while pulling the trolleys. For example, pulling an empty half-size trolley on a horizontal surface led on average to higher values of lumbar load than pulling it on an 8° inclined floor.

Bennett et al. (2008) examined the effect of gradient (0° and 12°) on the biomechanical responses in the form of hand forces during dynamic trolley pushing and pulling. Hand forces were found to be the highest during uphill initial and sustained phases and the downhill sustained phase. The authors suggested that sustained forces may be appropriate in determining the inherent potential risk of graded pushing; accordingly, for the sustained phase, there was no difference between uphill and downhill forces but level forces were significantly lower (18.9 ± 8.09 N) than either of the other two conditions. The investigation of pushing along graded ramps indicated that for all motion phases, forces exhibited during uphill and/or downhill efforts were significantly greater than those elicited during level pushing. Specifically, uphill pushing was the most taxing during the initial phase, while downhill pushing imposed the greater stress on the musculoskeletal system during the ending phase; for the sustained phase, hand forces for

both graded conditions were higher compared to level pushing. Hence, it is recommended that level pushing is preferable over graded pushing.

The aforementioned studies demonstrate that there is a relationship between gradient and the biomechanical load in terms of hand forces (Glitsch, et al., 2007; Bennett, et al., 2008) or lumbar-disc compression forces (Jäger, et al., 2007). Clearly, limited research is available regarding pushing and pulling along inclined walkways, despite a high prevalence of such tasks in a wide range of industrial settings.

2.5.3 Direction of force application

The direction of force application during the pushing/pulling was found to affect the musculoskeletal loading and has been identified as an important factor during the task assessment (van der Beek, et al., 1999; De Looze, et al., 2000). There can be four possible situations: (1) forward pushing with the vehicle in front of the operator (2) backward pulling with the vehicle in front of the operator, (3) forward pulling with the vehicle behind the operator and (4) forward pulling with the vehicle in front of the operator (on ramps). One-handed forward pulling and two-handed backward pulling are common as workers can use their body weight to assist in initial force production (Ayoub & Mcdaniel, 1974). Li et al. (2008) proposed that the use of one or two hands during pulling is related to load, such that at low loads workers tend to pull forwards with one hand; however when the load exceeds this capacity, two handed pulling is commonly used or preferred.

Schibye et al. (2001) investigated the (1) forward pushing with the waste container in front of the body and (3) forward pulling with the container behind the body. The calculated compression forces at L4L5 were rather small in all situations (605-1445 N). The reason that the stress on the lower back was rather small was that the forward trunk lean offsets the extension moment resulting from pushing and pulling forces. The compression force at L4L5 was smaller during pushing than during pulling. Forward pulling of carts resulted in twisted and laterally bent trunk postures (Frings-Dresen, Kemper, Stassen, Markslag, et al., 1995; Frings-Dresen, Kemper, Stassen, Crolla, et al., 1995; De Looze, et al., 1995) and required 9% more force than forward pushing

(Schibye, et al., 1997). It also caused greater spinal loading due to the shorter moment arm between the hand and the L4L5 disk for the extension moment that did not offset the flexion moment (Schibye, Sogaard, et al., 2001). However, forward pulling is more commonly used by operators because of better visibility, easier steering, and decreased muscle fatigue (Jung, et al., 2005).

Forward pushing was found to be less stressful than backward pulling (Jung, et al., 2005; De Looze, et al., 2000). Lee et al. (1991) indicated that backward pulling stressed the L5S1 two times higher than forward pushing. In the study of Jäger et al. (2007), forward pushing and backward pulling with the trolley in front of the body were utilized by the participants. Regardless of different surface inclinations and trolley loadings, no lumbar overload risk was found for pushing, whereas exceeding the recommended limit was frequently established for pulling the half size trolleys.

2.6 Musculoskeletal Models for Pushing and Pulling

The purpose of the present study was to evaluate the 3D musculoskeletal loading of major body joints and segments during dynamic pushing and pulling task. In the following section, biomechanical methods used for quantifying musculoskeletal loading during the pushing and pulling tasks are reviewed.

Direct measurement of mechanical load on the musculoskeletal system is very difficult. Biomechanical models are commonly used to predict mechanical stress on the musculoskeletal system (Hoozemans, et al., 1998). The models are relatively simple representations of the human body, because assumptions on the anatomical structures have to be made. With respect to pushing and pulling, risk factors for musculoskeletal disorders can be identified when biomechanical models predict an increase in mechanical stress. If the mechanical stress exceeds the load-bearing capacity of certain structures, the structures can get damaged and musculoskeletal disorders may develop (Kumar, 1990).

2.6.1 Single equivalent muscle models

Loads on the lumbar spine are mainly determined by muscle forces. Estimation of these loads is hampered by the fact that the muscle forces cannot be calculated, since the

many muscles crossing the lumbar spine form a statically indeterminate system when submaximal net moments are produced (van Dieen & de Looze, 1999). Biomechanically based spine models have been developed to help assess occupationally related manual material handling (MMH) tasks. One of the early static assessment models was developed by Chaffin at the University of Michigan. Both two-dimensional (2D) as well as three-dimensional (3D) static models (Chaffin and Muzaffer, 1991) have been developed to assess the risk of injury during MMH activities. In both models, the moments imposed upon the various joints of the body due to the object lifted are evaluated, assuming a static posture is representative of the instantaneous loading of the body. These models assume that a single equivalent muscle (internal force) supports the external moment about each joint. By considering the contribution of the externally applied load and the internally generated single muscle equivalent, spine compression acting on the lumbar discs is predicted. The 2D version of this computer model assumes that all lifts occur directly in front of the worker in the sagittal plane. Another important assumption of these models is that no significant motion occurs during the exertion because it is a static model. The 3D version of the computer model works in a similar manner; however, non-sagittal symmetric lifting assumptions are permitted. Figure 2.4 (University of Michigan, 2011) shows the output screen for this computer model where the lifting posture, lifting distances, strength predictions, and spine compression forces are shown.

Figure 2.4: The screenshot of 3DSSPP window after the posture was entered (University of Michigan, 2011)

A limited number of studies have employed biomechanical models in an attempt to calculate forces on the lower lumbar spine or shoulder during pushing and pulling exertions (Knapik & Marras, 2009). Resnick and Chaffin (1995) used such a single equivalent muscle model - a 2D dynamic biomechanical model developed by the University of Michigan to examine the pushing and pulling of carts weighing between 45-450 kg. The peak compression forces at the L5S1 spinal disc were computed using the sum of the dynamic external forces at the L5S1 disc and the pseudo-dynamic internal forces at the L5S1 disc based on the dynamic moment and static contractile forces on the erector spinae and rectus abdominal muscles. Calculated static compression forces at the L5S1 spinal disc were consistently above the NIOSH action limit of 3400 N (about 5000 N) for strong subjects when pushing carts over 225 kg. Spine shear forces were not reported in the study. De Looze et al. (1995) employed a 2D dynamic model of the upper body with a single extensor muscle to evaluate pushing and pulling of three different refuse collecting methods. On the basis of movement analysis, force measurements and biomechanical modeling, spinal compression, and shear forces were estimated. The peak compression and shear force in tilting/pushing and pulling mini-containers ranged from 1657 to 2654 N and from 123 to 248 N respectively. Another study of refuse collectors

employing a quasi-static 2D link segment model reported that the calculated compression forces at L4/L5 were rather small and ranged between 605-1445 N and the corresponding shear forces were below 202 N when transferring a load of 50 Kg (Schibye, Søgaaard, et al., 2001). In a similar type of study Laursen & Schibye (2002) evaluated the effect of pushing and pulling a two-wheeled waste containers on different surfaces: flagstones, paving stones, and grass. It was reported that the lumbar spine compression force was below 1800 N and the shear force was below 200 N in all situations. The shoulder torque when pulling with one hand was up to 80 Nm. In a recent study of Jäger et al. (2007), a biomechanical model ("THE DORTMUNDER") was used quasi-statically for quantifying the mechanical load on the lumbar spine. However, this model has restrictions for use. For example, it was used quasi-statically so that inertial effects of body-mass acceleration on lumbar load were neglected.

In all the aforementioned studies, static/quasi-static 2D, single equivalent muscle models were employed. This type of biomechanical model would not be sensitive to the trunk muscle co-contraction expected during dynamic pushing and pulling activities (Lee, et al., 1989; Knapik & Marras, 2009; Andres & Chaffin, 1991). One of the significant simplifying assumptions inherent in these static models is that the coactivation of the trunk musculature during the dynamic MMH activities is negligible. The trunk is truly a multiple muscle system with many major muscle groups supporting and loading the spine. Studies have demonstrated that there is a significant coactivation occurring in many of the major trunk muscle groups during dynamic lifting activities. This coactivation is important because all the trunk muscles have the ability to load the spine. Coactivation of trunk muscles provides joint stiffening, stability and controlled movement; however, coactivation also substantially increases mechanical loads such as compression and shear forces on lumbar spine (Garg & Kapellusch, 2009). Thus, assumptions regarding single equivalent muscles within the trunk can lead to erroneous conclusions about spine loading during a task. The study of Granata and Marras (1995a) reported that those biomechanical analyses that neglected muscle coactivity during dynamic lifting exertions might underestimate the spine compression force by as much as 45% and shear force by as much as 70%. In an effort to more accurately estimate the

loads on the lumbar spine, especially under complex, changing or dynamic exertions, multiple muscle systems models will be essential to assess the risk of injury.

2.6.2 EMG-assisted multiple muscle system models

In order to overcome such limitations as static or quasi-static mechanics, inaccurate prediction of muscle coactivity, neglecting the role of muscle co-contraction in quantifying spine loads, one of the few means to accurately account for the effect of the trunk muscle system coactivation upon spine loading is through the use of biologically assisted models. The most common of these models are dynamic and electromyography (EMG)-assisted models. These models take into account the individual recruitment patterns of the muscles during a specific lift for a specific individual. By directly monitoring muscle activity, the EMG-assisted model can determine individual muscle force and the subsequent spinal loading. These models have been developed and tested under bending and twisting dynamic motion conditions and have been validated in their ability to predict spine loads in three dimensions of loading during dynamic lifting activities (Marras & Granata, 1997a, 1995; Granata & Marras, 1995b; Marras & Sommerich, 1991a, 1991b; Granata & Marras, 1993).

The EMG-driven models “employ dynamic load in the hands, kinematic input, moment about the three axes of the low back normalized EMG, muscle-cross section area, a gain factor to represent muscle force per unit area and modulation factors describing EMG and force behavior as a function of muscle length and velocity to determine tensile load in each muscle” (Garg & Kapellusch, 2009). Input data required by these EMG-driven models include time-domain EMG, exertion kinetics, and kinematics. Maximum exertion EMG levels and subject anthropometry were also employed to calibrate and format the dynamic data suitable for use in the model mechanics. The cross-sectional area of each muscle was computed from regression equations based on the subject’s trunk depth and breadth. Trunk velocity was computed from dynamic measures of trunk flexion, twist, and lateral angles collected from a lumbar motion goniometer (lumbar motion monitor or LMM). Collected kinematic data were used in the model to: (1) describe the trunk motion as a function of time, (2) determine

the muscle force and moment vector directions, and (3) modulate muscle EMG values to account for muscle length and velocity artifact. The time-domain myoelectric data collected from trunk muscles such as the right and left latissimus dorsi, erector spinae, rectus abdominus, internal abdominal obliques, and external abdominal obliques represent muscle activity and were used to calculate relative muscle force. An example of the EMG-assisted model is shown in Figure 2.5.

Figure 2.5: An example of the EMG-assisted model (Marras & Granata, 1997b)

However, these EMG-driven biomechanical models have seldom been used to assess pushing and pulling because they have been optimized for back extension activities as opposed to the flexion and complex loading conditions expected during pushing and pulling (Knapik & Marras, 2009). Knapik and Marras (2009) demonstrated that it is possible to assess risk associated with pushing and pulling activities by employing an EMG-assisted model to account for trunk muscle coactivation in assessing spine loading at the various lumbar spine levels. The model used kinematic information about the trunk along with EMG information from the trunk musculature to estimate spinal loads, as well as predict the moments imposed on the spine in 3D space. Another study of Hoozemans et al. (2004) used a different EMG-driven biomechanical model (van Dieen, 1997; van Dieen & Kingma, 1999) to estimate compression and shear forces

at the L5S1 intervertebral disc. However, this study focused primarily upon the portion of the exertion (e.g., initial effort vs. sustained exertion) that yielded the largest loads on the spine (Knapik & Marras, 2009).

One limitation of such EMG-assisted models is that they require significant instrumentation on the worker, such as the Lumbar Motion Monitor (LMM) and several pairs of Ag/AgCl surface electrodes attached to the involved trunk muscles. These instrumentations may restrict human movement. Another limitation of such models is that it is not a comprehensive full-body musculoskeletal model. Such EMG-driven models are limited to assessing the loading on the lumbar spine. The loading of various other major body joints and segments cannot be explored by these models.

CHAPTER 3: RESEARCH RATIONALE

3.1 Problem Statement

With the advancement in the field of e-commerce in recent years, most manufacturing is done offshore, and there has been an increase in the number of distribution centers in the United States. At the distribution centers, workers primarily receive and transfer goods, and this has changed the way physical forces are being applied at the workplace. In the United States, nearly half of MMH activities common at workplaces demand pushing and pulling exertions (Hoozemans, et al., 2002b). In many other instances, pushing/pulling loads using assistive devices or interfaces such as trolleys, carts, trucks, wheelbarrows, etc., are the intervention strategies used to prevent lifting and carrying loads to reduce excessive loading of the lumbosacral (L5S1) joint, advocated as the weakest link in the vertebral column. Thus, pushing/pulling exertions are becoming increasingly predominant at various workplaces. Some epidemiological studies suggest that work-related pushing/pulling exertions are associated with musculoskeletal disorders of the low back (Hoozemans, et al., 1998; van der Beek, et al., 1993; Ozguler, et al., 2000; Klein, et al., 1984; Harber, et al., 1987; Garg & Moore, 1992; Fuortes, et al., 1994; Frymoyer, et al., 1980; Damkot, et al., 1984; NIOSH, 1997, 1981), shoulder, and other upper extremities (Hoozemans, et al., 1998; van der Beek, et al., 1993; Smedley, et al., 2003; Hoozemans, et al., 2002a, 2002b; Hughes, et al., 1997). Although epidemiological studies provide important indications as to the causality of the association, experimental studies are essential to estimate the quantitative information required to understand the process of how exposure may lead to musculoskeletal disorders (Hoozemans, et al., 2004; Keyserling, 2000).

Our literature review of experimental studies that evaluate pushing/pulling exertions identified the following research gaps:

- 1) Early studies that evaluated musculoskeletal loading primarily focused on static exertions. Recent dynamic pushing/pulling exertions were evaluated to examine changes in the hand forces or physiological parameters, such as heart rate and oxygen uptake or 2D low back and shoulder loading. A variety of studies in this field have investigated hand force exertion with particular concern toward the three motion phases (initial, sustained, and ending phases).

- 2) Past research studies have employed biomechanical models, such as single equivalent muscle models (Schibye, Sjøgaard, et al., 2001; Resnick & Chaffin, 1995; Laursen & Schibye, 2002; De Looze, et al., 1995) and EMG-assisted biomechanical models (Hoozemans, et al., 2004; Knapik & Marras, 2009) to quantify the loading of the lumbar spine during pushing and pulling. The 3D loading of the various other major body joints and segments using a more comprehensive full-body musculoskeletal model has not been explored.
- 3) Load weight is the most frequently studied task parameter during pushing/pulling exertions due to the strong linear relationship between biomechanical loading and load weight (Glitsch, et al., 2007; Jäger, et al., 2007; Hoozemans, et al., 2004; Laursen & Schibye, 2002). Limited research is available regarding pushing/pulling along ramps despite the prevalence of such tasks at workplaces.
- 4) Furthermore, past studies did not look at the changes in the biomechanical demands associated with uphill pushing and downhill pulling exertions along graded walkway.

The current study was aimed to quantify musculoskeletal loading during dynamic pushing and pulling exertions under varying task demands. The effect of three task parameters: load weight, walkway gradient, and direction of force exertion on the three-dimensional (3D) musculoskeletal loading of the lumbosacral (L5/S1) joint of the low back and three major shoulder joints (sternoclavicular, acromioclavicular, and glenohumeral) were studied using a full-body biomechanical modeling technique.

3.2 Objectives

The purpose of this study, quantification of musculoskeletal loading associated with dynamic pushing and pulling exertions under varying task demands, would be achieved through the following objectives:

Objective 1: evaluation of the effect of load weight transferred during pushing/pulling exertions on the 3D loading of the low back and shoulder joints

This objective would be achieved by studying pushing and pulling tasks performed using a most commonly used two-wheeled cart under three weight conditions: 20, 30, and 40 kg, in the

laboratory setting. These weights represent the loads displaced with the cart during material handling activities that are common at various workplaces.

Objective 2: evaluation of the effect of walkway gradient during pushing/pulling exertions on the 3D loading of the low back and shoulder joints

This objective would be achieved by studying pushing/pulling along a flat, 5°, and 10° ramped walkway, in the laboratory setting. The gradients represent the ramps that are normal at various workplaces.

Objective 3: evaluation of the effect of the direction of force exertion along ramps during pushing/pulling exertions on the 3D loading of the low back and shoulder joints

This objective would be achieved by studying pushing/pulling along the ramps, uphill and downhill, respectively. The cart was pushed or pulled in front of the human body.

3.3 Research Hypotheses

The role played by the load weight, walkway gradient, and direction of force exertion during dynamic cart pushing and pulling tasks were evaluated by testing five hypotheses. The hypothesis statements are as follows:

3.3.1 Hypothesis 1: Impact of load weight

The musculoskeletal loading of major low back and shoulder joints would increase, corresponding to the increase in the load weight displaced by the cart. The joint loading during displacing the load weight of 20, 30, and 40 kg along the same walkway was used to test this hypothesis.

3.3.2 Hypothesis 2: Impact of walkway gradient

The musculoskeletal loading of major low back and shoulder joints would increase, corresponding to the increase in the gradients when displacing the cart along the walkway. The joint loading at the same weight condition, during cart pushing over flat (0°) and two ramped (5° and 10°) walkways and during cart pulling over the two ramped (5° and 10°) walkways was used to test this hypothesis.

3.3.3 Hypothesis 3: Impact of direction of force application along the ramp

The musculoskeletal loading of major low back and shoulder joints would be higher during downhill pulling than during uphill pushing along the ramps. The joint loading during cart uphill pushing and downhill pulling tasks along the ramps of 5° and 10° while moving the same load was used to test this hypothesis.

3.3.4 Hypothesis 4: Low back loading in anterior-posterior direction

The low back loading at the L5S1 joint level in the anterior-posterior (AP) direction would be significantly affected by the pushing/pulling exertions evaluated in this study. . At the extreme task conditions (higher ramp, higher weight) the loading of the L5S1 joint in the anterior-posterior (AP) direction may exceed the recommended tolerance limit of this joint The L5S1 joint loading in AP direction during cart uphill pushing and downhill pulling tasks along the ramps of 5° and 10° while moving the same load was used to test this hypothesis.

3.3.5 Hypothesis 5: Shoulder loading at acromioclavicular joint

The musculoskeletal loading at the acromioclavicular joint would be significantly affected by the weight, gradient, and direction of force application during the pushing and pulling tasks. The overall loading of this joint would be comparable with the loading of the glenohumeral joint during the pushing/pulling exertions evaluated in this study.

CHAPTER 4: METHODS

4.1 Approach

The effect of dynamic pushing/pulling tasks on musculoskeletal loading was examined by performing a laboratory-based study. Human participants performed cart pushing/pulling tasks on a flat and two inclined walkways under three weight conditions: 20, 30, and 40 kg. Whole body 3-D joint kinematics and ground reaction force data were recorded using an eight-camera marker-based optical motion analysis system coupled with two ground reaction force platforms. The experimental data were used for running a full-body musculoskeletal model to compute the biomechanical loading of the low back at the L5/S1 level and three shoulder joints (sternoclavicular, acromioclavicular, and glenohumeral).

4.2 Participants

In order to control the confounding effect of the gender factor, only male participants were recruited in the study. In addition, men are more likely to be exposed to manual material handling tasks in real workplaces. Other pushing and pulling studies that used only male subjects include Bennett et al. (2008), De Looze et al. (2000), Hoozemans et al. (2004), Kuijer et al. (2002), Laursen and Schibye (2002), Lett and McGill (2006), and Schibye et al. (2001).

Twelve male participants with no history of musculoskeletal abnormalities participated in this study. The physical Activity Readiness Questionnaire (PAR-Q, British Columbia Ministry of Health) was used to screen participants for cardiac and other health problems (e.g., dizziness, chest pain, heart trouble) (Appendix A). Participants who answered yes to any of the questions on the PAR-Q were excluded. Prior to data collection, the experimental procedures and the demands of testing were explained to the participants, and their signatures were obtained on the informed consent form approved by the Institute Review Board at West Virginia University (Appendix B).

4.3 Experimental Design

This study consisted of two experimental sessions. In session one, the effect of load weight on biomechanical loading of low back and shoulder joints was evaluated. In session two,

the effects of load weight, walkway gradient, and direction of force application on biomechanical loading of the low back and shoulder joints were evaluated. A 3×2×2 full factorial experimental design was used. During both sessions, three trials of each experimental condition were recorded and the trial order was randomized.

4.3.1 Independent variables

In session one, participants performed cart pushing on a flat walkway. The load weight and the individual participants (treated as a block) were the independent variables. The load weight had three fixed levels: “light” load weight of 20 kg, a “medium” load weight of 30 kg, and a “heavy” load weight of 40 kg.

In session two, participants performed uphill pushing or downhill pulling tasks at three weight conditions along two gradients of walkway. The independent variables were: load weight, walkway gradient, and direction of force application. The levels of load weight were the same as in session one. Walkway gradient had two fixed levels: 5° and 10°, and direction of force application also had two fixed levels: uphill pushing or downhill pulling.

4.3.2 Dependent variables

Low Back Loading at the L5S1 joint: The lumbar spine is often a site of pain associated with forceful work activities. The L5S1 joint of the spine was chosen as the analysis of low back loading, because it is the lumbar joint that is expected to undergo the most stress (Kingma & van Dieen, 2004). The peak reaction forces acting at this joint in three anatomical directions: compression (proximal-distal), anterior-posterior (AP) shear, and medio-lateral (ML) shear were treated as the dependent variables for low-back loading. The abbreviations used for these dependent variables are as follows:

L5S1MedioLateral Force – L5S1-ML

L5S1Proximal-Distal Force – L5S1-PD

L5S1Anterior-Posterior Force – L5S1-AP

Shoulder Joint Loading: The shoulder complex consists of three joints: (1) sternoclavicular joint (SC); (2) acromioclavicular joint (AC); and (3) glenohumeral joint (GH). A brief anatomical description of these joints is provided in the literature review chapter (see

Section 2.3). The common work-related pathologies associated with the shoulder complex include: shoulder tendinitis, rotator cuff pain, and nonspecific shoulder pain. Repetitive loading of shoulder joints has been identified as one of the causal factors for these shoulder complex pain syndromes (NIOSH, 1997). Therefore, loading of the shoulder joint was assessed by using peak reaction forces acting in three anatomical directions at sternoclavicular joint, acromioclavicular, and glenohumeral joints. Table 4.1 lists the dependent variables used for studying shoulder joint loading.

4.3.3 Statistical models

The current study was divided into two sessions: (1) the load weight was evaluated for whether or not the increases of the weight transferred (20, 30, and 40 kg) by the cart increases participants' low-back and shoulder joint loading when they pushed the cart along a horizontal walkway; (2) the load weight, walkway gradient, and direction of force application were evaluated for whether or not the increases of the weight transferred (20, 30, and 40 kg), the gradient of the ramp (5° and 10°), and whether the changes of direction of force exertion along the ramps (uphill pushing and downhill pulling) increased participants' low-back and shoulder joint loading when they pushed/pulled the cart along ramps. The two sessions were evaluated respectively, and two statistical models were built as below:

Model 1 for session one along the flat walkway:

$$yF_{il} = \mu + \alpha_i + \gamma_l + \epsilon_{il} \quad \begin{cases} i = 1, \dots, a \\ l = 1, \dots, n \end{cases}$$

Where,

yF represents the low back and shoulder joints loading for pushing exertions along the flat walkway.

μ is the overall mean common to all observations.

α_i is the effect of load weight transferred by the cart pushed by the subjects, $i = 1, 2, 3$.

γ_l is the effect of subjects, $l = 1, 2, \dots, 12$.

ϵ_{il} is a random error term.

Table 4.1: Dependent variables used for studying shoulder joint loading

<p>Right SternoClavicular joint:</p> <p>Medio-Lateral Force – RSC-ML Inferior-Superior Force – RSC-IS Anterior-Posterior Force – RSC-AP</p>	<p>Inferior-Superior (IS)</p> <p>Medio-Lateral (ML)</p> <p>Anterior-Posterior (AP)</p> <p>SternoClavicular joint (SC)</p>
<p>Right AcromioClavicular joint:</p> <p>Medio-Lateral Force – RAC-ML Inferior-Superior Force – RAC-IS Anterior-Posterior Force – RAC-AP</p>	<p>Inferior-Superior (IS)</p> <p>Medio-Lateral (ML)</p> <p>Anterior-Posterior (AP)</p> <p>AcromioClavicular joint (AC)</p>
<p>Right GlenoHumeral joint:</p> <p>Distraction Force – RGH-DIS Inferior-Superior Force – RGH-IS Anterior-Posterior Force – RGH-AP</p>	<p>Inferior-Superior (IS)</p> <p>Distraction (DIS)</p> <p>Anterior-Posterior (AP)</p> <p>GlenoHumeral Joint (GH)</p>

Model 2 for session two along ramps:

$$yR_{ijkl} = \mu + \alpha_i + \beta_j + \tau_k + \gamma_l + (\alpha\beta)_{ij} + (\alpha\tau)_{ik} + (\beta\tau)_{jk} + (\alpha\beta\tau)_{ijk} + \epsilon_{ijkl} \quad \begin{cases} i = 1, \dots, a \\ j = 1, \dots, b \\ k = 1, \dots, c \\ l = 1, \dots, n \end{cases}$$

Where,

yR represents the low back and shoulder joint loading during cart pushing and pulling exertion along the ramped walkways.

μ is the overall mean common to all observations.

α_i is the effect of weight transferred by the cart pushed by the subjects, $i = 1, 2, 3$.

β_j is the effect of walkway gradient, $j = 1, 2$.

τ_k is the effect of direction of force application along ramps, $k = 1, 2$.

γ_l is the effect of subjects, $l = 1, 2, \dots, 12$.

$(\alpha\beta)_{ij}$ is the interaction effect of weight transferred by the cart and walkway gradient.

$(\alpha\tau)_{ik}$ is the interaction effect of weight transferred by the cart and direction of force application along ramps.

$(\beta\tau)_{jk}$ is the interaction effect of walkway gradient and direction of force application along ramps.

$(\alpha\beta\tau)_{ijk}$ is the interaction effect of the three factors: weight transferred by the cart, walkway gradient, and direction of force application along ramps.

ϵ_{ijkl} is a random error term.

In the first model, the load weight transferred (α_i) was treated as a fixed factor. It was assumed that this factor had no effect on the 3D loading of low back and shoulder joints during the cart pushing tasks along the flat walkway. That is:

$$\sum_{i=1}^a \alpha_i = 0.$$

Subjects (γ_l) were treated as a random factor, and it was assumed that it is NID ($0, \sigma_\gamma^2$) random variable. Random error ϵ_{il} followed NID ($0, \sigma^2$).

One table of analysis of variance (ANOVA) was provided for each response variable in this model (Appendix I). Therefore, the appropriate F tests were applied to test the means of the fixed factor, i.e., effects of the load weight transferred by the cart are equal, such as:

$$H_0: \alpha_1 = \alpha_2 = \alpha_3 = 0$$

$$H_1: \text{at least one } \alpha_i \neq 0$$

In this model, the Type I error $\alpha = 0.05$ and Power of the test ($1-\beta$), which equals 0.90, were chosen for the hypothesis test and sample size determination in Section 4.3.4.

In the second model, the load weight transferred (α_i), walkway gradient (β_j), and direction of force application along ramps (τ_k) were treated as fixed factors. It was assumed that each factor and the two-way or three-way interaction factors had no effect on the 3D loading of low back and shoulder joints during the uphill pushing or downhill pulling tasks along the ramps. That is:

$$\begin{aligned} \sum_{i=1}^a \alpha_i &= 0, & \sum_{j=1}^b \beta_j &= 0, & \sum_{k=1}^c \tau_k &= 0, \\ \sum_{i=1}^a \sum_{j=1}^b (\alpha\beta)_{ij} &= 0, & \sum_{i=1}^a \sum_{k=1}^c (\alpha\tau)_{ik} &= 0, & \sum_{j=1}^b \sum_{k=1}^c (\beta\tau)_{jk} &= 0, \end{aligned}$$

and

$$\sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c (\alpha\beta\tau)_{ijk} = 0.$$

Subjects (γ_l) were treated as a random factor, and it was assumed that it is NID ($0, \sigma_\gamma^2$) random variable. Random error ϵ_{il} and ϵ_{ijkl} followed NID ($0, \sigma^2$).

ANOVA tables were provided for each response variable in this model (Appendix J). Therefore, the appropriate F tests were applied on testing the means of the fixed factor effects are equal, such as

$$H_0: \alpha_i = 0, \beta_j = 0, \tau_k = 0 \text{ and}$$

$$(\alpha\beta)_{ij} = 0, (\alpha\tau)_{ik} = 0, (\beta\tau)_{jk} = 0, \text{ and } (\alpha\beta\tau)_{ijk} = 0,$$

$$H_1: \text{at least one } \alpha_i \neq 0, \beta_j \neq 0, \tau_k \neq 0 \text{ and}$$

$$\text{at least one } (\alpha\beta)_{ij} \neq 0, (\alpha\tau)_{ik} \neq 0, (\beta\tau)_{jk} \neq 0, \text{ and } (\alpha\beta\tau)_{ijk} \neq 0,$$

In this model, the Type I error $\alpha = 0.05$ and Power of the test $(1-\beta)$, which equals 0.90, were chosen for the hypothesis test and sample size determination in 4.3.4.

4.3.4 Power analysis and sample size determination

Operating characteristics curves (OC curves), a graph of β (type II error probability) versus the true difference in means, play an important role in the choice of sample size in experimental design problems. Therefore, the OC curves were used to do a power analysis and to determine the number of subjects to be recruited in this research.

The random factor subject (γ_1) was treated as a block, so determining the number of subjects was actually calculating the number of blocks. For both Model 1 and Model 2, the OC curves were used with the formula:

$$\lambda = \sqrt{1 + \frac{c\sigma_\gamma^2}{\sigma^2}}$$

where,

$$\sigma_\gamma^2 = \text{MSBL}, \sigma^2 = \text{MSE}.$$

History data were collected from five subjects ($c = 5$) performing both sessions. MSBL and MSE were calculated. Appendix C shows more detailed calculations of the sample size required for both parts of the study to achieve the required power of at least 0.90.

For the first model, by using OC curves, it was found that $\beta \approx 0.5$. Therefore, the power of the test was approximately $(1 - \beta) = 1 - 0.5 = 0.5$, which is less than the pre-selected power of at least 0.90. Table 4.2 shows the power for different number of subjects for Model 1 (pushing along the flat walkway). Note that eight subjects give a β risk of about 0.1, or approximately a

90% chance of rejecting the null hypothesis, and we can conclude that the load weight transferred by the cart (20, 30 and 40 kg) had an effect on the low back and shoulder joints.

Table 4.2: Power values for different number of subjects for Model 1

c	λ	β	Power (1-β)
5	2.05	0.5	0.5
6	2.2	0.34	0.66
7	2.34	0.2	0.8
8	2.48	0.1	0.9

Proceeding in a similar manner, for the second model, it was found that $\beta \approx 0.57$. Therefore, the power of the test was approximately $(1 - \beta) = 1 - 0.57 = 0.43$, which is also less than the pre-selected power of at least 0.90. Table 4.3 shows the power for a different number of subjects for Model 2 (uphill pushing and downhill pulling along the ramp). Note that eight subjects give a β risk of about 0.1, or approximately a 90% chance of rejecting the null hypothesis, and we can conclude that the factors considered in this part of the study, such as load weight transferred by the cart (20, 30 and 40 kg), walkway gradient (5° and 10°), and direction of force application along the ramps (uphill pushing and downhill pulling), had main effects on the low back and shoulder joints.

Table 4.3: Power values for different number of subjects for Model 2

c	λ	β	Power (1-β)
5	1.76	0.57	0.43
6	1.87	0.4	0.6
7	1.98	0.19	0.81
8	2.08	0.1	0.9

Therefore, eight subjects would be sufficient for both sessions of the current study to insure both power requests for the two models. However, we slightly increased the sample size to twelve subjects to guard against the possibility that the prior estimate of the standard deviation was too conservative.

4.4 Equipment

In this study, the following pieces of equipment (Figure 4.1) were used for data collection, processing, and analysis: (1) a hand truck and three loads, (2) a wooden walkway, (3) a scissor lift table, (4) four bottle jacks, (5) two force plates, (6) an eight-camera optical motion capture system, and (7) a musculoskeletal modeling system.

Figure 4.1: Equipment used for data collection, processing and analysis

4.4.1 Hand truck and loads

A two-wheeled Harper hand truck (CSLEDTK1935P, Harper Trucks, Inc., Wichita, KS, USA) (Figure 4.2) was used in this study. This is a standard, easily available and most commonly used hand truck in industrial settings (Keyserling, et al., 1999). This hand truck (1.25m height $\times$ 0.31m depth $\times$ 0.33m width) weighs 14.3 kg and has a capacity of 700 lbs. The height of the handle is 1.25m above ground level with the cart in an upright position and about

0.85 m in a tilted position ready to be moved. Each wheel, made of rubber, is a 10-inch pneumatic tire. In the current study, the coefficient of friction for rubber wheels on a wooden walkway was estimated to be approximately 1.3.

Figure 4.2: Hand truck used in this study attached with four reflective markers

4.4.2 Wooden walkway, scissor lift table and bottle jacks

A flat walkway (Figure 4.3 (a)) measuring 3 feet (wide) $\times$ 12 feet (length) was created using a reinforced wooden frame with cut-outs to accommodate the force plates (Figure 4.5). A hydraulic scissor lift table (EHLT-4872-3-43, Vestil Manufacturing Corp., IN, USA) (Figure 4.4 (a)) was attached to one end of the wooden walkway using a hinge assembly. This table has a collapsed height of 7" and can be raised to a maximum height of 36." When completely collapsed, it flushes with the walkway providing a flat walking surface. To set up the 5° (Figure 4.3 (b)) and 10° (Figure 4.3 (c)) ramped walkways, the table height was raised to 12.6" and 25" using a hydraulic actuator. The capacity of the lift table was 3,000 lbs, which is sufficient to support the weight of the wooden walkway and the participant performing the dynamic cart

pushing or pulling. In addition, the 48" (width) $\times$ 72" (length) top surface of the scissor lift table provided enough space for the participant to rest between trials.

While the ramp is in use, it is critical that it maintains both its strength and structural integrity. This is not only of paramount importance for safety, but also it is crucial so that the participant does not sense any anxiety-provoking motion in the ramp. If the participants are not comfortable walking on the ramp, they may be apprehensive and walk with an unnatural gait while pushing/pulling the cart. This may affect the quality of the ground reaction force (GRF) data. To prevent all these issues, the structure of the frame was designed to be stiff and rigid. Furthermore, four hydraulic bottle jacks (Torin Jacks, Inc., Ontario, CA) shown in Figure 4.4 (b) were used to support the walkway in the ramped configurations to improve its structural rigidity. The bottle jacks used in this study had a capacity of six tons and two of them were placed under each side of the inclined walkway close to the area where force plates were mounted.

4.4.3 Force plates

Two Kistler force plates (type 9286, Kistler Instrument Corp., Amherst, NY, USA) configured with the optical motion system were used to record the ground reaction force (GRF) (Figure 4.5) (Fischer, Kirchberg, & Moessner, 2009; You, et al., 2001; Janz, et al., 2003; Desailly, et al., 2009). Each plate, made of aluminum, weighs about 18 kg, measuring 60 cm (length) $\times$ 40 cm (width) $\times$ 3.5 cm (height). The force plate sensors use strain gauges to measure the three components of force in the x, y, and z and the corresponding moments around three orthogonal axes. The GRF data, collected at a frequency of 100 Hz, were synchronized with the kinematic data recorded using the optical motion analysis system. The surface of the force plates was flushed with the walkway to accurately measure GRF as the participant makes contact with the force plate. Figure 4.5 shows the actual placement of the two force plates in the walkway. The two force plates were mounted in the walkway with an offset of 20 cm to allow acquisition of GRF of right and left foot steps during normal gait. In addition, this offset of 20 cm also allowed recognition of footsteps independent of force vectors exerted by the cart, which is essential for accurately running the biomechanical modeling analysis.

Figure 4.3: Wooden walkway: (a) flat; (b) 5° ramp; (c) 10° ramp

Figure 4.4: (a) Scissor lift table; (b) hydraulic bottle jacks to minimize the GRF data noise

Figure 4.5: Two force plates embedded in wooden platform

4.4.4 Optical motion capture system

Figure 4.6: Pictures of a Vicor MX camera

This is an eight-camera optical motion analysis system (Vicor Oxford Metrics, UK). Figure 4.6 shows the front and side views of a Vicor MX camera. Each camera records 3D motion trajectories of the small reflective balls (markers) attached to the participants, at a frequency of 100 Hz.

Figure 4.7: 14 mm (0.55 inch) reflective markers

Light emitted from infrared sources mounted near the cameras is reflected off the markers and captured by the cameras. The markers are lightweight and interfere minimally with the subject's movements (Figure 4.7). The eight video cameras were placed around the walkway to create a capture volume. Each marker is simultaneously imaged by multiple cameras and the location of the marker in the 3D space (x, y, z coordinates) is computed using triangulation by the Vicon Nexus software.

A Plug-in Gait (PIG) marker set was used for the kinematic data collection in this study. PIG is the Vicon implementation of the Conventional Gait Model which is widely used by the gait analysis community and has been validated in a number of studies (Andreoni, et al., 2009; Hwang & Kim, 2009; Riley, et al., 2007; Kojima, Nakajima, & Takada, 2008). PIG uses a defined marker set and a set of subject measurements to create joint kinematics and kinetics output. There are a total of 39 markers used in a PIG marker set. The marker locations used in the PIG marker set are shown in Figure 4.8. The 39 markers include 4 markers on the head, 5 markers on the torso, 7 markers on each arm, 4 markers on the pelvis, 4 markers on each leg, and 2 markers on each foot. The anatomical locations of these markers are listed in Table 4.4. In addition to the PIG marker set, four markers (diameter = 3.5cm) were placed on the cart in order to capture its motion relative to the participant during the pushing and pulling tasks (Figure 4.2).

Figure 4.8: Marker locations used in the Plug-in Gait (PIG) marker set

Table 4.4: Anatomical locations of Plug-in Gait marker set

Upper Body Markers	
<u>Markers:</u>	<u>Location:</u>
LFHD / RFHD	Left and right side of the forehead
LBHD / RBHD	Left and right side of the back of the head
CLAV	Jugular notch at the proximal aspect of the sternum
STRN	Xyphoid process at the distal aspect of the sternum
C7	Spinous process of the 7 th cervical vertebrae
RBAK	Mid scapula
T10	Spinous process of the 10 th thoracic vertebrae
LSHO / RSHO	Tip of the left and right acromion processes
LUPA / RUPA	Approximately 1/3 of the distance from the shoulder to the elbow, and slightly to the posterior
LELB / RELB	Lateral epicondyle of the humerus
LFRM / RFRM	Midpoint of the front of the forearm, between the radius and ulna
LWRA / RWRA	Medial aspect of the wrist (thumb side)
LWRB / RWRB	Lateral aspect of the wrist (pinky side)
LFIN/RFIN	Distal aspect of the third metacarpal on the back of the hand
Lower Body Markers	
<u>Markers:</u>	<u>Location:</u>
LASI / RASI	Anterior superior iliac spine
LPSI / RPSI	Lateral aspect of pelvis, at the most superior point of the Ilium
LTHI / RTHI	Approximately 1/3 of the distance from the greater trochanter to the knee, and slightly to the posterior
LKNE / RKNE	Lateral condyle of the knee
LTIB / RTIB	Approximately 1/3 of the distance from the knee to the ankle, and slightly to the posterior
LANK / RANK	Lateral malleolus of the tibia
LHEE/RHEE	On the back of the heel
LTOE / RTOE	Distal aspect of the third metatarsal on the top of the foot

4.4.5 AnyBody modeling system

To quantify the biomechanical loading of the low back and shoulder joints during the pushing/pulling tasks, musculoskeletal models were formulated using the AnyBody modeling system (AnyBody Technology, Aalborg, Denmark). AnyBody modeling system uses AnyScript

modeling language to formulate detailed musculoskeletal models. The syntax of AnyScript is similar to C++ programming language. It is an object-oriented programming language developed specifically for defining bones (or segments) with different geometries, different types of anatomical joints, muscles with real physiological properties, and an accurate line of actions. The joints in the AnyBody modeling system are driven by using different types of drivers. These drivers can be operated using mathematical functions or experimentally collected kinematic data, and the resulting joint loading is calculated using inverse dynamics analysis.

In biomechanics, especially in gait studies, inverse dynamics analysis is traditionally used to calculate net moments at the lower extremity joints by using experimentally recorded ground reaction forces. Inverse dynamic analysis involves computation of unknown forces by using known motion equations. Due to the redundancy of the muscle actuator configuration, the muscle recruitment problem is formulated as an optimization problem. The usual solution is to recruit muscles to minimize some criterion. The AnyBody modeling system employs a minimum muscle fatigue criterion (Rasmussen, Damsgaard, & Voigt, 2001), leading to a numerically efficient algorithm for calculating the internal forces in the body. The inverse dynamics analytical process in the AnyBody system is illustrated in Figure 4.8 (Rasmussen, Damsgaard, & Christensen, 2001).

Figure 4.9: Inverse dynamic analytical process implemented by AnyBody modeling system

A public-domain repository of human body models is available which eliminates the need to build the human anatomy over again for each application. By using the model scaling utility, the model can be scaled to match individual anthropometry. The generic AnyBody model comprises of:

- (i) an arm and shoulder complex model with 114 muscle fascicles on each side,
- (ii) a lumbar spine model comprising the sacrum, all lumbar vertebrae, and a total of 158 muscles fascicles,
- (iii) a rigid thoracic spine section,
- (iv) a cervical spine model comprising 136 muscles fascicles,
- (v) a pelvis and lower extremity model with a total of 326 muscles fascicles.

Thus, the whole human body model consists of over 750 individual muscle fascicles, 33 joints, and 34 rigid body segments. AnyBody musculoskeletal models have been used previously to estimate musculoskeletal loading during manual material handling tasks (Wagner, Rasmussen, & Reed, 2007), shoulder joint forces while operating a wheelchair (Dubowsky, et al., 2008), index finger loading during computer keyboard tapping (Wu, et al., 2008), and lower limb joint movements during stilt walking of construction workers (Wu, Chiou, & Pan, 2009). The AnyBody modeling system also allows the adding of physical entities in the environment of the human model to evaluate human interaction with different interfaces. Some previous studies have evaluated human interaction with bicycles, furniture, sports equipment, hand tools, etc. In the present study, a hand truck and loads were modeled in the environment file which was connected to the human model.

4.5 Data Collection Procedures

The data collection session for each participant consisted of the following steps:

(1) Before the arrival of participants, a set of calibration routines for the optical camera system and force platforms were performed.

(i) Camera calibration: This involved three steps. The first step, static camera calibration, required reading the location of the markers on the static calibration object – “L frame” (Figure 4.10 (a)) by all the cameras. During this step, it was essential that only the “L-frame” markers were visible to the cameras, and no other reflective objects were present in the capture volume. This “L frame” was placed at a specific corner of one of the two force platforms. The second step involved calibrating the capture volume. During this step, the “L-frame” object was removed from the capture volume and a 240 mm camera calibration wand with three reflective markers (Figure 4.10 (b)) was used. An experimenter slowly moved the wand in a three-dimensional motion for about 1 to 2 minutes throughout the entire capture volume to be calibrated. The system then processed the calibration data and reported on the accuracy and precision of the calibrated volume. It is recommended to achieve accuracy (Mean Residual) of less than 1.000 mm and a static reproducibility of less than 1.000%. The final step of camera calibration involved setting the origin of the capture volume. To set the origin, the “L-frame”

was placed at the predetermined corner of one of the force plates, and through Vicon Nexus software, proper options were selected to set the origin of the capture volume.

(ii) Force platform calibration: The force plate setting in the Vicon Nexus software was checked for accuracy of the calibration matrix and gain factor. The six analog channels (F_x , F_y , F_z , M_x , M_y , M_z) of each force plates were then zeroed. The experimenter then walked across the plates to ensure that all the plates were feeding correct information to the analog system.

Figure 4.10: (a) Static calibration object – “L frame”; (b) 240 mm camera calibration wand

(2) Upon participants’ arrival to the laboratory, each participant was shown the experimental set up (walkway, cart, force plates, optical motion capture system, and loads to be transferred with cart) and a brief explanation of the research objectives was provided. They were then asked to read and sign an informed consent form, in accordance with the West Virginia University’s IRB policy statement.

(3) Participants then changed to the test shirt and shorts and a set of demographic and anthropometric measurements were recorded. A list of anthropometric variables measured in this study is shown in the Table 4.5. Some of these measurements are required by Vicon Nexus software to form a real time stick figure of the participants during data collection, while others are required to formulate the model using the AnyBody system.

Table 4.5: Required subject anthropometric measurements

	Required subject measurements	
	For Vicon	For AnyBody modeling
General	Body mass (in kg) Height (in cm)	
Upper body (in cm)	<u>Shoulder offset</u> : vertical distance from the center of the glenohumeral joint to the marker on the acromion clavicular joint <u>Elbow width</u> : distance between the medial and lateral epicondyles of the humerus <u>Wrist width</u> : distance between the ulnar and radial styloids <u>Hand thickness</u> : distance between the dorsal and palmar surfaces of the hand	<u>Head height</u> : height in neutral position from C1Hat node to top of head <u>Trunk height</u> : C1Hat node to L5S1 joint <u>Upper arm length</u> : distance in neutral position from acromioclavicular joint to elbow joint <u>Forearm length</u> : distance in neutral position from elbow joint to wrist joint <u>Hand length</u> : distance from wrist to tip of fingers <u>Hand breadth</u> : distance between the medial and lateral sides of the hand
Lower body (in cm)	<u>Leg length</u> : distance between ASIS and medial malleolus, via the knee joint <u>Knee width</u> : distance between the lateral and medial femoral epicondyles <u>Ankle width</u> : distance between the medial and lateral malleoli	<u>Pelvis width</u> : distance between hip joints <u>Thigh length</u> : distance between ASIS to knee joint <u>Shank length</u> : distance between knee joint and ankle joint <u>Foot length</u> : distance between the heel and the toe of the foot

(4) The next step in the data collection was to attach the thirty-nine reflective markers on the participant at various anatomical locations using the Vicon Plug-in Gait marker set. The Vicon Skeleton Template (.vst), which is the generic definition of the human skeleton, was used for performing the static subject calibration. The original Vicon Skeleton Template “Plug-in Gait full body.vst” was modified by adding a cart segment with four markers to create a “Cart.vst” model template. This modified template file was then used for collecting and processing the kinematic data.

(5) Prior to the initiation of experimental testing, the participant stood in a static T-pose to be captured by Vicon as a calibration trial. No motion capture should be started until verification that all tracking markers were visible during this step. Upon finishing the calibration trial, participants performed several practice trials to become familiar with the experimental tasks.

(6) The participants then performed the experimental trials. The trial order was randomized. Participants were instructed to begin each push/pull task with both feet together, by standing straight and holding the cart handle with two hands. At a verbal signal from the experimenter, participants pushed/pulled the cart along the walkway from the start to the ending position. The data were recorded for each trial during the experiment and stored on the computer for later data processing. Duration of a trial was approximately 15 to 20 seconds. A rest period of 1 minute was provided between the trials. Owing to the submaximal nature of the exertions, this rest period was sufficient to allow full recovery. A participant mounted with the reflective markers performing cart pushing/pulling experimental trials is shown in Figure 4.11.

Figure 4.11: Participant performing cart pushing/pulling tasks along (a) a flat walkway, (b) a ramped walkway while going uphill, and (c) a ramped walkway while going downhill

4.6 Data Processing

4.6.1 Kinematic data: Vicon Nexus software

The marker data were processed using Vicon Nexus motion software. In this software, each marker was labeled and a corresponding human model was created by performing the steps as follows:

(i) Reconstruction and cropping:

The 3D positions were computed by reconstruction of the trial. It may take time to fully reconstruct the entire trial. Before labeling the trajectories in the motion trials, unwanted data that were outside the duration of the analysis were cropped.

(ii) Trajectory identification and gap filling:

To label the trajectories, a static 3D view of the marker is used. The markers were identified manually by selecting a marker from the 3D view and then selecting its four letter marker name from the list obtained from the .vst model template. As the markers were identified, blue lines were added automatically to join markers that are part of the head and trunk segment, whereas red and green lines added to joint markers of the left and right upper/lower body, respectively. The four markers of the cart were also identified and added with yellow lines. Once all markers were identified, we checked that all the trajectories were joined without any gaps. If a marker turned white, it was manually labeled. Next, all the gaps were filled and any unlabeled trajectories were deleted. Figure 4.12 shows the last step of checking the marker labeling and gap filling. Finally, the trial data were exported and saved in C3D file format, which consisted of 43 markers and force plates' analog data. The C3D file was imported to AnyBody modeling system to run the full body musculoskeletal model.

(iii) Angle outputs:

The Vicon Nexus software can output the joint angles of major body joints, such as the trunk, hip, knee, ankle, shoulder, elbow, and wrist. The output angles for all joints were calculated from YXZ cardan angles derived by comparing the relative orientations of the two segments (Vicon). In the current study, the peak flexion/extension values of trunk, right shoulder, right elbow, right hip, right knee, and right ankle were exported. Table 4.6 shows the angle definitions for the exported flexion/extension angles.

Figure 4.12: The human model performing cart pushing/pulling tasks created by Vicon Nexus software:(a) pushing along the flat walkway; (b) uphill pushing along a ramp; (c) downhill pulling along a ramp

Table 4.6: Definitions of exported joint angles

Angle	Definition
Trunk Flexion/Extension	Trunk flexion is the angle between the sagittal thorax axis and the sagittal pelvis axis around the fixed transverse axis of the pelvis. A positive (Flexion) angle value corresponds to the situation in which the thorax is tilted forward.
Shoulder Flexion/Extension	Shoulder flexion is calculated about an axis parallel to the thorax transverse axis. Shoulder flexion is the angle between the projected sagittal-humerus axis and the sagittal-thorax axis around the fixed transverse axis of the thorax. A positive (Flexion) angle value corresponds to the situation in which the arm is in front of the body.
Elbow Flexion/Extension	Elbow flexion is the only kinematic parameter calculated at the elbow as the segment definitions of the Humerus and radius result in two of the axes being shared. Elbow flexion is calculated between the sagittal radius axis and the sagittal humerus axis around the fixed transverse axis of the humerus. A positive number indicates a flexion angle.
Hip Flexion/Extension	Hip flexion is calculated about an axis parallel to the pelvic transverse axis which passes through the hip joint centre. The sagittal thigh axis is projected onto the plane perpendicular to the hip flexion axis. Hip flexion is then the angle between the projected sagittal thigh axis and the sagittal pelvic axis. A positive (Flexion) angle value corresponds to the situation in which the knee is in front of the body.
Knee Flexion/Extension	The sagittal shank axis is projected into the plane perpendicular to the knee flexion axis. Knee Flexion is the angle in that plane between this projection and the sagittal thigh axis. The sign is such that a positive angle corresponds to a flexed knee.
Ankle Flexion/Extension	The foot vector is projected into the foot sagittal plane. The angle between the foot vector and the sagittal axis of the shank is the Foot Dorsi/Plantar Flexion. A positive number corresponds to dorsiflexion.

4.6.2 Musculoskeletal model simulation

The AnyBody modeling system caters to a wide range of users with very different modeling needs. Some may simply want to load and run an existing model, some may need to modify the model to a smaller or larger extent, and some may want to build their own model bottom-up. Most users can find themselves in one of the following scenarios:

- Loading a model from the model repository and changing simple parameters like the load.
- Modifying one of the existing motion capture models from the repository to the lab setup.
- Modifying a model from the repository by redefining the environment.
- Constructing a body model and its environment bottom-up.

In the present study, the musculoskeletal modeling was based on one of the existing motion capture models (Gait Full Body Model) from the model repository (Version 1.2 of AnyBody Managed Model Repository, AMMRV1.2). The structure of the repository is shown in Figure 4.13:

Figure 4.13: Structure of AnyBody repository

Note: (1) Applications are the models that can be loaded into AnyBody and simulate biomechanical situation.

(2) Body contains models of body parts and collection of body parts which are used by the applications. The entire body model contains many hundreds of muscles, and it is rather heavy computationally.

(3) Beta folder contains models that are unfinished but may be of value to users with special interests.

(4) Example folder contains many models of different situations.

(5) Validation folder contains models that have been used for validation purposes, typically by comparison of the model predictions with experimental measurements.

(6) AAUHuman contains the Aalborg university full body model, while AUHuman contains a mandible model developed in Aarhus University, and Beta refers to other research groups and the non-human models.

We modified the Gait Full Body model to our own laboratory setup by redefinition of the marker protocol (adding four markers of the cart), redefinition of the environment (the force platforms, the cart as an additional segment definition), and matching initial posture and individual anthropometrics for each participant. The modified “Cart Push Pull” model was loaded to simulate the dynamic cart pushing/pulling tasks. A kinematic optimization and inverse dynamic analysis was then operated; lastly, the joint loading in the form of joint reaction forces of low back at L5S1 level and three major shoulder joints (SC, AC, and GH) was saved and exported into a data sheet. Figure 4.14 shows the structure of the model with the kinematic and inverse dynamic studies used for running and quantifying the musculoskeletal loading, respectively.

Figure 4.14: Structure of the musculoskeletal model and details of the kinematic and inverse dynamic analysis studies

The following sections provide a detailed description of the model.

4.6.2.1 “Model Setup”

“Model Setup” file contains coding for the definition of the input file (C3D file), the marker topology, and linkage between the free floating markers in the C3D file with the markers on the human body.

(i) Definition of the input file to the analysis:

This step was executed by using “AnyInputC3D”, “AnyString” and “AnyFunButterworthFilter” terms to connect to the C3D file.

(ii) Redefinition of the marker topology of the C3D file:

The existing file contains the definition of thirty-nine markers shown in Figure 4.8: Plug-in Gait (PIG) marker placement protocol. However, the present study had four more markers attached on the cart to capture the motion of the cart during the tasks, shown in Figure 4.2. Therefore, we will add the definitions of the four markers of the cart in the “Model Setup” file. The collected C3D file from the optical motion analysis system was named as “CARTRU,” “CARTLU,” “CARTRL,” and “CARTLL,” which are defined as below:

```
CreateMarkerCart CARTRU (  
  MarkerName=CARTRU,  
  MarkerPlacement = Cart,  
  OptX="Off",OptY="Off",OptZ="Off",  
  WeightX=1.0,WeightY=1.0,WeightZ=1.0,  
  Model1=MotionAndParameterOptimizationModel, Model2= InverseDynamicModel  
)= {  
  sRelOpt = {0.115,0.16,0.70};  
};  
  
CreateMarkerCart CARTLU (  
  MarkerName=CARTLU,  
  MarkerPlacement = Cart,  
  OptX="Off",OptY="Off",OptZ="Off",  
  WeightX=1.0,WeightY=1.0,WeightZ=1.0,  
  Model1=MotionAndParameterOptimizationModel, Model2= InverseDynamicModel  
)= {  
  sRelOpt = {0.115,-0.16,0.70};  
};  
  
CreateMarkerCart CARTRL (  
  MarkerName=CARTRL,
```

```

MarkerPlacement = Cart,
OptX="Off",OptY="Off",OptZ="Off",
WeightX=1.0,WeightY=1.0,WeightZ=1.0,
Model1=MotionAndParameterOptimizationModel, Model2= InverseDynamicModel
)= {
sRelOpt = {0.115,0.16,0.47};
};

CreateMarkerCart CARTLL (
MarkerName=CARTLL,
MarkerPlacement = Cart,
OptX="Off",OptY="Off",OptZ="Off",
WeightX=1.0,WeightY=1.0,WeightZ=1.0,
Model1=MotionAndParameterOptimizationModel, Model2= InverseDynamicModel
)= {
sRelOpt = {0.115,-0.16,0.47};
};

```

Figure 4.15: Model statement for defining the four markers attached on the cart

sRelOpt is the relative position of the marker at the cart interface. The three coordinate values (x, y, and z) were input according to the measurement between the center of the mass (cart and load) and marker positions.

(iii) Optimization control about anthropometrics and marker location:

Except the head height and varus-valgus anthropometrics, other segmental anthropometrics data such as pelvis width, thigh length, shank length, foot length, trunk height, upper arm length, and lower arm length were optimized when running the kinematic optimization study. The AnyScript like “OptX,” “OptY,” and “OptZ,” shown in the definition of the above “CARTRU” marker box, determines if the design variable (x, y, or z coordinate of sRelOpt) was to be optimized (“On”) or left unchanged in parameter optimization study (“Off”).

```

OptimizeAnthropometricsOnOff OptimizeOnOff (
PelvisWidthOnOff ="On",
ThighLengthOnOff="On",
ShankLengthOnOff="On",
FootLengthOnOff="On",
HeadHeightOnOff="Off",
TrunkHeightOnOff="On",
UpperArmLengthOnOff="On",
LowerArmLengthOnOff="On",
VarusValgusOnOff="Off",
Model1=MotionAndParameterOptimizationModel, Model2= InverseDynamicModel)

```

Figure 4.16: Model statement for parameter optimization control

4.6.2.2 “Trial Specific Data”

(i) Reading the C3D data file for the analysis:

This step was executed by using the “AnyString” term to input the C3D file name (e.g., “Subject name – 0 degree – 20 kg – Trial 1”, “Subject name – 5 degree – 20 kg – pushup – Trial 1”, “Subject name – 10 degree – 20 kg – pushup – Trial 1”, etc.)

(ii) Controlling the start and end time:

It was essential to identify the frames in the C3D file corresponding to the heel contact of the first foot with the force platform and toe off of the other foot from the force platform, to accurately run the model. These frames were identified manually and assigned to the tstart and tend values in the trial specific part of the model.

```
AnyString NameOfFile = "YY-5 degree -20kg-pushup-Trial1"; // to change the name of the C3D file accordingly

//Starting time for the analysis calculated from C3D data but can be changed is needed
AnyFloatVar tStart =
Main.ModelSetup.C3DFileData.Header.FirstFrameNo/Main.ModelSetup.C3DFileData.Header.VideoFrameRate+1.
7; //to start from the time the first foot touching the plate by adjusting the time manually

//End time for the analysis calculated from C3D data but can be changed is needed
AnyFloatVar tEnd =
Main.ModelSetup.C3DFileData.Header.LastFrameNo/Main.ModelSetup.C3DFileData.Header.VideoFrameRate-
0.15; //to end from the time the last foot leaving the plate by adjusting the time manually
```

Figure 4.17: Model statements for controlling file name, start and ending time

(iii) Input individual anthropometrics data:

Here the anthropometric measurements were input to match each participant. These data were used as an initial guess for the optimization algorithm that would allow changes to the segmental lengths in the study of kinematic optimization.

```
AnyFolder Anthropometrics= {
  AnyVar BodyMass=63; //the mass is automatically distributed to the segments
  AnyVar BodyHeight=1.72; //height
  AnyVar ThighLength= 0.47; //right and left side is mirrored
  AnyVar ShankLength= 0.38;
  AnyVar FootLength=0.27;
  AnyVar PelvisWidth=0.23; //distance between hip joints
  AnyVar HeadHeight = 0.15; //height in neutral position from C1HatNode to top of head
  AnyVar TrunkHeight = 0.54; //height in neutral position from C1HatNode to L5SacrumJnt
```

```

AnyVar UpperArmLength = 0.275;
AnyVar LowerArmLength = 0.27;
AnyVar HandLength = 0.182;
AnyVar HandBreadth = 0.088;
};

```

Figure 4.18: Model statement for inputting individual anthropometric measurements

(iv) Input initial position of body and its posture

The position of the human body, which is defined by angles of “PelvisRotZ,” “PelvisRotY,” and “PelvisRotX,” was adjusted to the C3D data’s XYZ coordinate system. Then based on the joint configuration in the frame corresponding to the tstart, the joint angles were adjusted to minimize the error in the marker locations at the load time.

```

AnyFolder InitialPositionOfBody = {
  AnyVar PelvisRotZ = 180;
  AnyVar PelvisRotY = 0;
  AnyVar PelvisRotX = 90; // to match the X, Y, Z coordinate system in the current laboratory setup
AnyFolder Right = {
  AnyVar GlenohumeralFlexion = 20; // best guess of initial posture for the participant
  AnyVar GlenohumeralAbduction = 0;
  AnyVar GlenohumeralExternalRotation = 10;
  AnyVar ElbowFlexion = 5;
  AnyVar ElbowPronation = 75.0;
  AnyVar WristFlexion = 55;
  AnyVar WristAbduction = 0;
  AnyVar HipFlexion = 20;
  AnyVar HipAbduction = 0;
  AnyVar HipExternalRotation = 0;
  AnyVar KneeFlexion = 0;
  AnyVar AnklePlantarFlexion = 0;
  AnyVar SubTalarEversion = 0 ;};
AnyFolder Left = {
  AnyVar GlenohumeralFlexion = 20;
  AnyVar GlenohumeralAbduction = 0;
  AnyVar GlenohumeralExternalRotation = 10;
  AnyVar ElbowFlexion = 5;
  AnyVar ElbowPronation = 75.0;
  AnyVar WristFlexion = 55;
  AnyVar WristAbduction = 0;
  AnyVar HipFlexion = -20;
  AnyVar HipAbduction = 0;
  AnyVar HipExternalRotation = 0;
  AnyVar KneeFlexion = 0;
  AnyVar AnklePlantarFlexion = 0;
  AnyVar SubTalarEversion = 0 ;};
};

```

Figure 4.19: Model statement for initial position and posture for participant

4.6.2.3 “Environment” around the human

The environment around the human was modified by adding a hand cart, reaction forces at the hand cart interface, two force plates and the corresponding ground reaction forces.

(i) Creating the hand cart as an additional segment

The cart was defined as a segment in the environment file by using the “AnySeg” object in AnyScript. It was defined as a rigid body, formed using eighteen nodes joined together using polyline object. Additionally, two nodes for the right and left handle were created to connect the cart with the hands. The mass properties of the cart were defined by means of a mass and an inertia tensor.

```
AnySeg Cart = {  
  
Mass = 34; // when the load weight is 20 kg  
// The cart weighs 14 kg. When the load weight is 30 kg, 40 kg, then Mass = 44, 54, respectively.  
  
Jii = {0.7076,0.541,0.5241}; //when the load weight is 20 kg  
//The inertial moment was calculated based on the three-dimension measurements of the cart and the loads.  
// When the load weight is 30 kg, then Jii = {1.0844, 0.8266, 0.726}; when the load weight is 40 kg, then Jii =  
//{1.6314, 1.2878, 1.022}.  
  
r0 = {-0.1241, 0.40,0.3872}; //the initial position guess of the cart  
Axes0 = RotMat(45*pi/180,y);  
AnyVec3 Color = .LoadRGB;  
AnyVar Opacity=0.3; //box opacity  
  
AnyVec3 Size={0.245,0.45,0.30}; // when the load weight is 20 kg  
//based on the three-dimension measurements of the load transferred by the cart  
//30 kg load weight size is {0.25,0.44,0.39}; 40 kg load weight size is {0.28,0.45,0.47}.  
  
#include "../Body/AAUHuman/ToolBox/DrawObjects/Box.any" //visualize the load in a box structure  
  
AnyRefNode RightWheelNode={  
    sRel={0.26,0.215,-0.05};  
};  
AnyRefNode LeftWheelNode={  
    sRel={0.26,-0.215,-0.05};  
};  
AnyRefNode CartNode = {  
    AnyRefNode Node0={  
        sRel={0.123,0,-0.15};  
    };  
};  
// 2 handles connected with hands  
AnyRefNode HandleLeft = {  
    sRel = {0.26,-0.14,1.09};  
};
```

```

AnyRefNode HandleRight = {
    sRel = {0.26, 0.14, 1.09};
};
AnyRefNode Node0={
    sRel={0.123,0.17,-0.15};
};
AnyRefNode Node1={
    sRel={0.123,0.17,0.0};
};
AnyRefNode Node2={
    sRel={0.123,0.17,0.32};
};
AnyRefNode Node3={
    sRel={0.123,0.17,0.64};
};
AnyRefNode Node4={
    sRel={0.123,0.17,0.84};
};
AnyRefNode Node5={
    sRel = {0.27,0.17,1.07};
};
AnyRefNode Node05={
    sRel={0.27,-0.17,1.07};
};
AnyRefNode Node04={
    sRel={0.123,-0.17,0.84};
};
AnyRefNode Node03={
    sRel={0.123,-0.17,0.64};
};
AnyRefNode Node02={
    sRel={0.123,-0.17,0.32};
};
AnyRefNode Node01={
    sRel={0.123,-0.17,0.0};
};
AnyRefNode Node00={
    sRel={0.123,-0.17,-0.15};
};
AnyRefNode Node7 = {
    sRel = {-0.123,-0.17,-0.15};
};
AnyRefNode Node07 = {
    sRel = {-0.123,0.17,-0.15};
};
AnyRefNode Node6 = {
    sRel = {0.0,-0.17,-0.15};
};
AnyRefNode Node06 = {
    sRel = {0.0,0.17,-0.15};
};
AnyFolder Line01 ={
    AnyRefFrame &node1=.Node6;
    AnyRefFrame &node2=.Node06;
    AnyDrawPLine line ={
        Thickness=0.03;

```

```

    RGB=...LoadRGB;
};
};
AnyRefNode Node002={
    sRel={0.26,-0.18,-0.05};
};
AnyRefNode Node0002={
    sRel={0.26,0.18,-0.05};
};
//Draw a visual line between the points
AnyFolder Line1 ={
    AnyRefFrame &node1=.Node0;
    AnyRefFrame &node2=.Node1;
    AnyRefFrame &node3=.Node2;
    AnyRefFrame &node4=.Node3;
    AnyRefFrame &node5=.Node4;
    AnyRefFrame &node6=.Node5;
    AnyRefFrame &node7=.Node05;
    AnyRefFrame &node8=.Node04;
    AnyRefFrame &node9=.Node03;
    AnyRefFrame &node10=.Node02;
    AnyRefFrame &node11=.Node01;
    AnyRefFrame &node12=.Node00;
    AnyDrawPLine line ={
        Thickness=0.025;
        RGB=...LoadRGB;
    };
};
AnyFolder Line2 ={
    AnyRefFrame &node1=.Node2;
    AnyRefFrame &node2=.Node02;
    AnyDrawPLine line ={
        Thickness=0.02;
        RGB=...LoadRGB;
    };
};
AnyFolder Line3 ={
    AnyRefFrame &node1=.Node3;
    AnyRefFrame &node2=.Node03;
    AnyDrawPLine line ={
        Thickness=0.02;
        RGB=...LoadRGB;
    };
};
AnyFolder Line4 ={
    AnyRefFrame &node1=.Node1;
    AnyRefFrame &node2=.Node01;
    AnyDrawPLine line ={
        Thickness=0.02;
        RGB=...LoadRGB;
    };
};
AnyFolder Line5 ={
    AnyRefFrame &node1=.LeftWheelNode;
    AnyRefFrame &node2=.Node002;
    AnyRefFrame &node3=.Node02;

```



```

AnyRefFrame &node4=.Node2;
AnyRefFrame &node5=.Node0002;
AnyRefFrame &node6=.RightWheelNode;
AnyDrawPLine line ={
    Thickness=0.02;
    RGB=...LoadRGB;
};
};
AnyFolder Line6 ={
    AnyRefFrame &node1=.Node00;
    AnyRefFrame &node2=.Node7;
    AnyRefFrame &node3=.Node07;
    AnyRefFrame &node4=.Node0;
    AnyDrawPLine line ={
        Thickness=0.02;
        RGB=...LoadRGB;
    };
};
AnyFolder Line7 ={
    AnyRefFrame &node1=.Node00;
    AnyRefFrame &node2=.Node002;
    AnyRefFrame &node3=.Node0002;
    AnyRefFrame &node4=.Node0;
    AnyDrawPLine line ={
        Thickness=0.02;
        RGB=...LoadRGB;
    };
};
//a linear measure of the cart motion to dump out translations of the cart
AnyKinLinear CartLin = {
    Ref = 0;
    AnyRefNode &ref1 = ..GlobalRef.GroundNode;
    AnyRefNode &ref2 = .CartNode;
};
//a rotational measure... to dump out rotations of the cart...
AnyKinRotational CartRot = {
    AnyRefNode &ref1 = ..GlobalRef.GroundNode;
    AnyRefNode &ref2 = .CartNode;
    Type=RotAxesAngles;
};
AnyKinMeasureOrg CartLinOrg = {
    AnyKinLinear &ref = .CartLin;
    MeasureOrganizer = {0};
};
};//Cart and Load definition

```

Figure 4.20: Model statement for definition and visualization of the hand cart used in the study

Figure 4.21: Cart model and hand/cart interface visualized in AnyBody modeling system

(ii) Definition of hand/cart interface with kinematic measures and contact forces

This step created kinematic measures (“AnyKinLinear” and “AnyKinRotational”) that allow movement tracking of the palm joint of each hand with respect to the cart. An AnyKinLinear measure can gauge the spatial vector between two points (nodes). The line Ref = 0 means that the coordinates of this linear distance were measured first in the coordinate system of the measure’s end points, which in this case was the cart’s right handle frame. An AnyKinRotational measure can gauge the rotation vector between two points. The contact force between the hand and the cart handle was added by using the “AnyReacForce” object.

The force equilibrium in the AnyBody modeling system is taken care of by the muscles and the reaction forces in the model. The reactions come as joint reactions or as AnyReacForce used in this study. The muscle recruitment algorithm attempts to lower the highest activated muscle; in this process the reaction forces are determined automatically. The reaction forces had no cost in the objective function, so the algorithm always tries to use the available reactions in order to lower the muscle activations as much as possible. Therefore, the AnyScript programming here for the hand/cart interface formulation was in principle a two-step procedure,

first the kinematic measures between the hand and the cart were solved, then the kinetics were resolved by determining the reaction forces at the hand/cart interface.

```
AnyKinLinear rLin = {
  AnyRefNode &CartNode = ..EnvironmentModel.Cart.HandleRight;
  AnyRefNode &HandNode = ...HumanModel.BodyModel.Right.ShoulderArm.Seg.Hand.PalmJoint;
  Ref = 0;
};

AnyKinRotational rRot = {
  AnyRefNode &CartNode = ..EnvironmentModel.Cart.HandleRight;
  AnyRefNode &HandNode = ...HumanModel.BodyModel.Right.ShoulderArm.Seg.Hand.PalmJoint;
  Type = RotVector;
  AngVelOnOff = On;
};

//added a reaction force between cart and hands
AnyReacForce RighthandCartForce = {
  AnyKinRotational &ref1=. rRot ;
  AnyKinLinear &ref2=. rLin ;
};

AnyKinLinear lLin = {
  AnyRefNode &CartNode = ..EnvironmentModel.Cart.HandleLeft;
  AnyRefNode &HandNode = ...HumanModel.BodyModel.Left.ShoulderArm.Seg.Hand.PalmJoint;
  Ref = 0;
};

AnyKinRotational lRot = {
  AnyRefNode &CartNode = ..EnvironmentModel.Cart.HandleLeft;
  AnyRefNode &HandNode = ...HumanModel.BodyModel.Left.ShoulderArm.Seg.Hand.PalmJoint;
  Type = RotVector;
  AngVelOnOff = On;
};

// added a reaction force between cart and hands
AnyReacForce LefhandCartForce = {
  AnyKinRotational &ref1=. lRot ;
  AnyKinLinear &ref2=. lLin ;
};
```

Figure 4.22: Model statement for the hand/cart interface formulation

(iii) Creating two force plates, and automatic detection of foot with correct force plate

The default force plate type in the Gait Full Body model was set as “Type 4,” which was the same as a “Type 2” force platform, except that a calibration matrix was being provided for it via the CAL_MATRIX parameter. Our C3D file does not have a calibration matrix data; as a result, the model was modified to execute a “ForcePlateType2AutoDetection” term to simulate

the two force plates and connected to the C3D file data (Fx, Fy, Fz, Mx, My, Mz). The term could automatically detect foot contact with force plate 1 or plate 2.

```
ForcePlateType2AutoDetection Plate1 (
PlateName = Plate1,
Folder =Main.ModelSetup.C3DFileData,
Limb1= ...HumanModel.BodyModel.Right.Leg.Seg.Foot,
Limb2= ...HumanModel.BodyModel.Left.Leg.Seg.Foot,
No=0,
VerticalDirection ="Z",
HeightTolerance=0.07,
VelThreshold=2.2,
Fx=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fx5,
Fy=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fy5,
Fz=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fz5,
Mx=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Mx5,
My=Main.ModelSetup.C3DFileData.Analog.DataFiltered.My5,
Mz=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Mz5)
={
//Cal=Main.ModelSetup.C3DFileData.Groups.FORCE_PLATFORM.CAL_MATRIX.Data[0];
};

ForcePlateType2AutoDetection Plate2 (
PlateName = Plate2,
Folder =Main.ModelSetup.C3DFileData,
Limb1= ...HumanModel.BodyModel.Right.Leg.Seg.Foot,
Limb2= ...HumanModel.BodyModel.Left.Leg.Seg.Foot,
No=1,
VerticalDirection ="Z",
HeightTolerance=0.07,
VelThreshold=2.2,
Fx=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fx6,
Fy=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fy6,
Fz=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Fz6,
Mx=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Mx6,
My=Main.ModelSetup.C3DFileData.Analog.DataFiltered.My6,
Mz=Main.ModelSetup.C3DFileData.Analog.DataFiltered.Mz6)
={
//Cal=Main.ModelSetup.C3DFileData.Groups.FORCE_PLATFORM.CAL_MATRIX.Data[1];
};
```

Figure 4.23: Model statement for auto detection of force plate touched by the foot steps

4.6.2.4 “Joint Angle Outputs”

The “Joint Angle Outputs” file automatically saved the optimized motion in text files named after the C3D file name. For example, the File Name was “Subject name-20 kg-push-10°-Trial 2-output-euler-trunk.txt.” Based on the existing setup for saving the optimized

motion, an output file for the cart motion was created so that the cart motion data was dumped out automatically for later inverse dynamic study use.

```
AnyOutputFile OutputFile1 = {
  FileName = Main.ModelSetup.C3DFileData.NameOfFile+"-output-euler-trunk.txt";
  SepSign = " ";
  AnyVector PelvisPosX = ..HumanModel.BodyModel.Interface.Trunk.PelvisPosX.Pos;
  AnyVector PelvisPosY = ..HumanModel.BodyModel.Interface.Trunk.PelvisPosY.Pos;
  AnyVector PelvisPosZ = ..HumanModel.BodyModel.Interface.Trunk.PelvisPosZ.Pos;
  AnyVector PelvisRotX = ..HumanModel.BodyModel.Interface.Trunk.PelvisRotX.Pos;
  AnyVector PelvisRotY = ..HumanModel.BodyModel.Interface.Trunk.PelvisRotY.Pos;
  AnyVector PelvisRotZ = ..HumanModel.BodyModel.Interface.Trunk.PelvisRotZ.Pos;
  AnyVector PelvisThoraxExtension = ..HumanModel.BodyModel.Interface.Trunk.PelvisThoraxExtension.Pos;
  AnyVector PelvisThoraxLateralBending =
  ..HumanModel.BodyModel.Interface.Trunk.PelvisThoraxLateralBending.Pos;
  AnyVector PelvisThoraxRotation = ..HumanModel.BodyModel.Interface.Trunk.PelvisThoraxRotation.Pos;
};
```

Figure 4.24: Model statement for automatic saving the motion data of the trunk

```
AnyOutputFile OutputFile0 = {
  FileName = Main.ModelSetup.C3DFileData.NameOfFile+"MyCartWheelPosition.txt";
  SepSign = " ";
  AnyVector CartPosLin =
  Main.Studies.KinematicStudyForParameterIdentification.EnvironmentModel.Cart.CartLin.Pos;
  AnyVector CartPosRot =
  Main.Studies.KinematicStudyForParameterIdentification.EnvironmentModel.Cart.CartRot.Pos;
  //a rotational measure
};
```

Figure 4.25: Model statement for automatic saving the cart motion data

4.6.2.5 “Joints and Drivers Optimized”

The “Joints and Drivers Optimized” file was used to automatically run the optimized motion in text files, which are already saved in the previous kinematic optimization study. Based on the existing file, a driver for the cart was created to control the motion of the cart in the inverse dynamic study with the use of “AnyKinEqInterPolDriver” term. This driver would read directly from the already saved text file.

```
AnyKinEqInterPolDriver JntDriverTrunk = {
  FileErrorContinueOnOff = On;
  Type = Bspline;
  BsplineOrder = 4;
  FileName = Main.ModelSetup.C3DFileData.NameOfFile+"-output-euler-trunk.txt";
  AnyKinMeasureOrg &PelvisPosX = ...HumanModel.Interface.Trunk.PelvisPosX;
  AnyKinMeasureOrg &PelvisPosY = ...HumanModel.Interface.Trunk.PelvisPosY;
```

```

AnyKinMeasureOrg &PelvisPosZ = ...HumanModel.Interface.Trunk.PelvisPosZ;
AnyKinMeasureOrg &PelvisRotX = ...HumanModel.Interface.Trunk.PelvisRotX;
AnyKinMeasureOrg &PelvisRotY = ...HumanModel.Interface.Trunk.PelvisRotY;
AnyKinMeasureOrg &PelvisRotZ = ...HumanModel.Interface.Trunk.PelvisRotZ;
AnyKinMeasureOrg &PelvisThoraxExtension = ...HumanModel.Interface.Trunk.PelvisThoraxExtension;
AnyKinMeasureOrg &PelvisThoraxLateralBending =
...HumanModel.Interface.Trunk.PelvisThoraxLateralBending;
AnyKinMeasureOrg &PelvisThoraxRotation = ...HumanModel.Interface.Trunk.PelvisThoraxRotation;
Reaction.Type={On,On,On,On,On,On,On,Off,Off,Off};
};

```

Figure 4.26: Model statement for running the optimized trunk motion data in inverse dynamic analysis step

```

AnyKinEqInterPolDriver JntDriverCart = {
FileErrorContinueOnOff = On;
Type = Bspline;
BsplineOrder = 4;
FileName = Main.ModelSetup.C3DFileData.NameOfFile+"MyCartWheelPosition.txt";
AnyKinLinear &ref1 = Main.Studies.InverseDynamicStudy.EnvironmentModel.Cart.CartLin;
AnyKinRotational &ref2 = Main.Studies.InverseDynamicStudy.EnvironmentModel.Cart.CartRot
Reaction.Type={Off,Off,Off,Off,Off,Off};
};

```

Figure 4.27: Model statement for running the optimized cart motion data in inverse dynamic analysis step

4.6.2.6 Running inverse dynamic study

Upon finishing all the aforementioned modeling steps, the system performed an actual inverse dynamic analysis based on the parameters identified in the previous MotionAndParameterOptimization step. This operation loaded the optimized model parameters that were saved previously; if necessary, it would perform calibration movements to adjust the tendon lengths to the lengths of the bones; and finally it executed an inverse dynamic analysis to determine forces in the system, as shown in Figure 4.19. When the analysis was complete, the ChartFX view would demonstrate all the biomechanical loading and muscle forces, and so on. The joint reaction forces at the L5S1, SC, AC, and GH joint were dependent variables in the present study. The output was exported into a series of data sheets for later statistical analysis.

4.7 Statistical Analysis

Minitab version 15 (Minitab Inc., PA, USA) was used to manage and analyze data in the current study. A general linear model with ANOVA (analysis of variance) was used to determine the effect of independent variables on the response variables.

In the first session where participants pushed the cart by varying the load weight along the flat walkway, the load weight was the single independent variable, which was treated as a fixed factor at three levels, while the subject was treated as a random factor. No interaction was evaluated in this simple general linear model (Model 1).

In session two where participants pushed or pulled the cart along the ramps by varying the load weight, walkway gradients and direction of force application along the ramps, there were three fixed factors: load weight (at three levels), walkway gradient (at two levels), and direction of force application (at two levels). Subjects were also treated as random factors in this model (Model 2). There were several two-way interaction factors (walkway gradient $\times$ load weight, walkway gradient $\times$ direction of force application, and load weight $\times$ direction of force application) and one three-way interaction factor (walkway gradient $\times$ load weight $\times$ direction of force application) included in the general linear model.

For both sessions, a post hoc trend analysis was performed using Tukey's HSD (Honestly Significant Differences) test to make All pair-wise comparisons (Appendix K). The significance level was set at 5%.

It was assumed that the random error of the ANOVA models were normally, identically, and independently NID ($0, \sigma^2$) distributed. Minitab can also generate residual plots to examine how well the linear model fit. Therefore, a normal probability plot of residuals and a histogram of residuals were used to test the assumption: error $\epsilon \sim \text{NID}(0, \sigma^2)$.

Figure 4.28: The biomechanical model used for quantifying the musculoskeletal loading created by the AnyBody modeling system: (a) pushing along the flat walkway; (b) uphill pushing along a ramp; (c) downhill pulling along a ramp

CHAPTER 5: MODEL VALIDATION

5.1 Introduction

Validating a musculoskeletal model is necessary. Muscle force patterns are typically compared to electromyography (EMG) activity patterns to validate the results of the musculoskeletal model (Erdemir, et al., 2007). For example, to validate an upper extremity musculoskeletal model, Morrow et al. (2010) and Dubowsky et al. (2008) compared the simulation results with the experimental EMG data for each subject during wheelchair activities using the mean absolute error between the EMG activity envelope and the predicted muscle activity from the model. In the study of Marras et al. (1991c), a three-dimensional EMG-assisted model was validated by comparing the calculated trunk torque with measured trunk torque during dynamic lifting exertions. Plamondon et al. (1996) examined the validity of two three-dimensional segment models to estimate the net reaction forces and moments at the L5S1 joint. By applying the models to lifting activities, results from the two models in terms of joint reaction forces and joint reaction moments at the L5S1 joint were compared between the two models. In a different study, De looze et al. (1992) used ground reaction force data to validate a two-dimensional dynamic linked segment model. The reaction forces predicted by the model were compared with measured vertical ground reaction forces during lifting activities to validate the biomechanical model. Similar to the study of De looze et al. (1992), the model output of cart wheel reaction forces in the current study were compared to experimentally recorded ground reaction force (GRF) data by the force plates to validate the modeling procedure.

5.2 Approach

The force equilibrium in the AnyBody modeling system is determined by the muscles and the reaction forces in the model. The accuracy of the computed cart wheel reaction forces will affect the output of muscle forces and joint reaction forces in the process of inverse dynamic analysis. Therefore, it is important to validate the accuracy of the predicted cart wheel reaction forces.

In this study, the ground reaction force (GRF) was recorded by the force plates at two instances: (1) when the cart wheel is moving over the force plates; (2) when the participant is

stepping on the force plates. The first part data will be used to conduct the validation. Since the experimental data is being used for running the musculoskeletal model, the part of the experimental data when the cart wheel is moving over the force plate needs to be zeroed. GRF platform measured cart wheel forces in three dimensions (F_x' , F_y' , F_z'). The Anybody musculoskeletal model used in this study output only the forces in the vertical direction (F_z). Therefore, the two vertical forces (F_z' and F_z) for the cart wheel were compared to validate the musculoskeletal model in this study.

On average, the duration for each cart wheel moving over the force plate was 0.6 ± 0.10 seconds. The minimum duration was approximately 0.5 seconds. The analog GRF data was recorded at a sampling rate of 100 Hz, meaning that 100 frames are equal to 1 second. Therefore GRF data corresponding to 50 frames from the C3D file were used as the reference for making the comparison. In the AnyBody modeling system, the start time was matched to the starting frame of the 50 chosen frames. For example, the 50 frames (from frame number 101 to frame number 150) were chosen as a reference in the experimentally recorded GRF data. After zeroing the load weight, the trial in C3D file format was loaded into the AnyBody modeling system. The start time was matched to the beginning frame number, by using “AnyFloatVar tStart = 101/Main.ModelSetup.C3DFileData.Header.VideoFrameRate.” The ending time of the AnyBody file was also matched to the ending frame, by using “AnyFloatVar tEnd = 150/Main.ModelSetup.C3DFileData.Header.VideoFrameRate.” When the cart wheel reaction forces data were exported from the AnyBody output, the first time column followed by the column of reaction forces data was shown in seconds from 1.01 to 1.50 seconds. Validity (accuracy) was then evaluated by determining the difference between the values during the same time period (time = 0.5 seconds) computed by the AnyBody modeling system and each frame of 50 frames obtained by the optical motion analysis system.

Figure 5.1: (a) Cart wheel is moving over the force plates; (b) the participant is stepping on the force plates

5.3 Methods

The original pipelined C3D data files from the optical motion analysis system were used as a reference to validate the accuracy of the simulated wheels' vertical forces by the AnyBody modeling system.

The process used to conduct the model validation consists of following steps:

(1) Kinematics data collection and processing:

In this step, marker and GRF data during pushing and pulling trials were recorded and processed using Vicon nexus software. The details of data collection and processing are mentioned in Methods chapter, Section 4.5 data collection procedures and Section 4.6.1 Kinematic data processing. Figure 5.1 (a) shows the two instances during which the GRF platform records the cart wheel forces and Figure 5.2 shows the processed kinematics data trial processed by the Vicon Nexus software. The two red arrows in the Figure 5.2 show the measured ground reaction forces.

(2) Zeroing the cart wheel forces:

The C3Deditor (Motion Lab Systems, Inc., LA, USA), a graphical, C3D file editing program, was used to edit the C3D files by zeroing the cart wheel forces. Figure 5.3 shows the distribution of ground reaction force (GRF) in the original C3D file output by the Vicon Nexus software when the participant pushed the load weight of 40 kg on the ramp of 5°. In the analog section of the original C3D file, the part of the frames reporting cart wheel GRF were identified, and the corresponding magnitudes were zeroed. Figure 5.4 shows the processed C3D file.

Figure 5.2: Kinematics data processed by the Vicon Nexus software, corresponding to the experimental trial shown in Figure 5.1(a)

Figure 5.3: The originally stored Analog data of cart wheels and human body shown by C3Deditor in Windows

Figure 5.4: The modified Analog data after zeroing the cart wheel forces shown by C3Deditor in Windows

(3) Model computations:

The modified C3D data were used to run the musculoskeletal model. Details of steps used to run the model are explained in the Methods chapter, Section 4.7.2. Inverse dynamic analysis was performed to compute vertical reaction forces for left and right cart wheels. Figure 5.5 shows the model statement used for calculating wheel forces, and Figure 5.6 shows a picture of the musculoskeletal model used to compute the cart wheels' vertical forces in the AnyBody modeling system platform.

```
AnyKinLinear rWheelLin = {
  Ref = 0;
  AnyRefNode &ref1 = .GlobalRef.GroundNode;
  AnyRefNode &CartNode = .Cart.RightWheelNode;
};
AnyKinMeasureOrg rWheelLinOrg = {
  AnyKinLinear &ref = .rWheelLin;
  MeasureOrganizer = {2}; // vertical is z direction
};
AnyReacForce RightWheelVerticalForce = {
// created a vertical force on the right side of cart
  AnyKinMeasureOrg &ref=.rWheelLinOrg;
};

AnyKinLinear lWheelLin = {
  Ref = 0;
  AnyRefNode &ref1 = .GlobalRef.GroundNode;
  AnyRefNode &CartNode = .Cart.LeftWheelNode
};
AnyKinMeasureOrg lWheelLinOrg = {
  AnyKinLinear &ref = .lWheelLin;
  MeasureOrganizer = {2}; // vertical is z direction
};
AnyReacForce LeftWheelVerticalForce = {
// created a vertical force on the left side of cart
  AnyKinMeasureOrg &ref=.lWheelLinOrg;
};
```

Figure 5.5: Model statement of computing cart wheels' vertical reaction forces

(4) Data processing:

Raw GRF data from force plates were low pass filtered by using a butter worth filter with the cutoff frequency of 5Hz. The forces during 50 frames (time = 0.5 seconds) of each experimental condition were chosen to be compared predicted forces with the experimental data to test the accuracy of the musculoskeletal model.

Figure 5.6: Picture of the musculoskeletal model used for computing cart wheels' vertical reaction forces

5.4 Data analysis

The data from six male participants (mean age = 23 ± 4 years; mean height = 1.70 ± 0.2 m; mean weight = 65.6 ± 12.3 kg) were used in this part of study to validate the accuracy of the musculoskeletal model. A procedure similar to Fong et al. (2008) was used for conducting the model validation computations. The vertical component of GRF (Fz') recorded by force plates was compared with the reaction force calculated by the model by using root mean squared error (RMSE) calculation (Fong, et al., 2008; Wong & Wong, 2008; Plamondon, et al., 2007). All of the differences were converted to a RMSE using the following equation:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (Fz_i - Fz'_i)^2 \right]^{1/2}$$

Where,

Fz the vertical forces computed by AnyBody modeling system,

Fz' the reference vertical forces measured by the GRF platform,

n the number of samples ($n = 50$ frames), and i the sample number ($i = 1, \dots, 50$).

In addition to the RMSE, the correlation coefficient (r) was also calculated to assess the accuracy of the computed wheel reaction forces using the following equation:

$$r = \frac{\sum_{i=1}^n (Fz_i - \overline{Fz})(Fz'_i - \overline{Fz'})}{\sqrt{\sum_{i=1}^n (Fz_i - \overline{Fz})^2} \sqrt{\sum_{i=1}^n (Fz'_i - \overline{Fz'})^2}}$$

Where,

Fz the vertical forces computed by AnyBody modeling system,

Fz' the reference vertical forces measured by the GRF platform,

n the number of samples ($n = 50$ frames), and i the sample number ($i = 1, \dots, 50$).

ANOVA tables (Appendix D) were provided to estimate the effect of load weight, walkway gradient, and direction of force application on the calculated RMSE and r .

5.5 Results

The minimum and maximum correlations between computed wheel reaction forces by AnyBody modeling system and the reference vertical forces measured by the GRF force plates were 0.837 and 0.987 respectively. On average, the correlation between the actual and estimated data was 0.919 and the average RMSE was 15.06 N, which was about 3.96% of the peak value recorded in all experimental conditions (380 N). The maximum RMSE across the subjects was 24.98 N (6.57% of the peak value) and the minimum RMSE was 8.83 N (2.32% of the peak value) (Table 5.1).

When participants performed the cart pushing tasks along the flat walkway, the calculated r and RMSE were not different from one another with respect to the three weight conditions ($p = 0.557$ for r ; $p = 0.074$ for RMSE). During uphill pushing and downhill pulling tasks the walkway gradient was found to have a significant effect on the computed correlation coefficient (r) ($p < 0.001$). The effect of load weight was found to be significant for the computed RMSE ($p = 0.005$). The direction of force application also had a significant effect on the RMSE ($p = 0.008$). In addition, there was a significant interaction effect of walkway gradient by direction of force application on the RMSE ($p = 0.016$).

Figures 5.7 – 5.11 show the pattern of the actual and computed wheel reaction forces for a selected number of trials and the corresponding absolute error. In general, the pattern of computed reaction forces matched very well with the actual data.

5.6 Discussion and Conclusion

In the current study, an existing comprehensive full-body musculoskeletal model was modified by redefinition of the marker protocol (adding four cart markers), adding force platforms, the lab coordinate system and most importantly, by creating a cart as a rigid segment in the environment of the model. Interaction of the cart with the human model and environment was established by setting contact forces between the hand and the cart handle and cart wheels' reaction forces. The reaction forces on the cart wheels contribute to the computation of the joint reaction and muscle forces in order to maintain the model equilibrium and therefore can be used for model validation purpose. Previously, De Looze et al. (1992) have used similar approach to validate a biomechanical model.

The results of the validation study show a high correlation between the actual and predicted cart wheel reaction forces (average = 0.919). The mean RMSE was 15.06 N, which was 3.96% of the peak value of 380 N. In the previous studies RMSE up to 6% of the peak value was reported to be acceptable (Fong, et al., 2008). Therefore, it was concluded that the musculoskeletal model developed in this study was accurately predicting the reaction forces and consequently the muscle and joint loading that resulted from its interaction with the cart.

Table 5.1: Accuracy of the computed left cart wheel's vertical forces as represented by the correlation coefficient (r) and the root mean square error (RMSE), and the peak forces measured by the GRF platform

Experimental Conditions	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6		All subjects		Peak force in all trials (N)
	r	RMSE	r	RMSE	r	RMSE	r	RMSE	r	RMSE	r	RMSE	r	RMSE	
0° – 20 kg	0.968	10.33	0.963	9.83	0.959	11.83	0.933	11.55	0.935	12.92	0.954	10.8	0.952	11.21	216
0° – 30 kg	0.975	8.83	0.967	9.67	0.981	11.16	0.952	14.69	0.864	15.88	0.969	9.81	0.951	11.67	319
0° – 40 kg	0.986	12.64	0.932	12.79	0.953	14.33	0.930	17.83	0.918	12.26	0.914	11.89	0.939	13.62	380
5°-20kg-up	0.966	8.93	0.968	10.03	0.948	9.3	0.846	19.22	0.895	20.08	0.963	10.55	0.931	13.02	220
5°-30kg-up	0.955	13.88	0.958	10.02	0.946	10.96	0.944	20.34	0.830	18.98	0.959	10.18	0.932	14.06	301
5°-40kg-up	0.957	14.72	0.933	13.97	0.955	10.68	0.968	22.78	0.896	21.78	0.854	8.54	0.927	15.41	371
5°-20kg-down	0.984	13.51	0.962	13.9	0.837	10.86	0.940	23.46	0.871	22.67	0.962	14.78	0.926	16.53	218
5°-30kg-down	0.948	13.82	0.952	15.14	0.927	11.02	0.908	21.94	0.842	23.42	0.946	15.69	0.921	16.84	288
5°-40kg-down	0.987	15.2	0.968	15.86	0.942	13.89	0.880	20.46	0.883	24.06	0.923	13.26	0.931	17.12	361
10°-20kg-up	0.912	15.27	0.949	12.08	0.876	12.49	0.933	12.92	0.902	24.24	0.948	12.69	0.920	14.95	220
10°-30kg-up	0.926	18.4	0.905	11	0.883	12.56	0.906	15.68	0.922	24.56	0.901	11.24	0.907	15.57	297
10°-40kg-up	0.961	17.33	0.938	15.21	0.863	14.27	0.845	19.9	0.852	24.24	0.841	13.87	0.883	17.47	354
10°-20kg-down	0.901	16.46	0.880	8.31	0.922	14.03	0.834	18.68	0.891	22.35	0.889	7.92	0.886	14.63	220
10°-30kg-down	0.863	15.2	0.947	11.62	0.914	12.39	0.900	17.08	0.840	24.98	0.928	15.23	0.899	16.08	267
10°-40kg-down	0.900	18.4	0.946	14.02	0.845	13.93	0.847	19	0.895	23.67	0.869	17.01	0.884	17.67	352
All	0.946	14.19	0.945	12.23	0.917	12.25	0.904	18.37	0.882	21.07	0.921	12.23	0.919	15.06	380

Figure 5.7: (a) – (c) The pattern of the actual and computed wheel reaction forces during pushing tasks performed at 20, 30, and 40 kg weight conditions on a flat walkway and the corresponding absolute error for averaged across the participants

Figure 5.8: (d) – (f) The pattern of the actual and computed wheel reaction forces during uphill pushing tasks performed at 20, 30, and 40 kg weight conditions on a gradient of 5° and the corresponding absolute error for averaged across the participants

Figure 5.9: (g) – (i) The pattern of the actual and computed wheel reaction forces during downhill pulling tasks performed at 20, 30, and 40 kg weight conditions on a gradient of 5° and the corresponding absolute error for averaged across the participants

Figure 5.10: (j) – (l) The pattern of the actual and computed wheel reaction forces during uphill pushing tasks performed at 20, 30, and 40 kg weight conditions on a gradient of 10° and the corresponding absolute error for averaged across the participants

Figure 5.11: (m) – (o) The pattern of the actual and computed wheel reaction forces during downhill pulling tasks performed at 20, 30, and 40 kg weight conditions on a gradient of 10° and the corresponding absolute error for averaged across the participants

CHAPTER 6: RESULTS

6.1 Subject Data

Participants in this study were in the age group of 21 to 28 years. All the participants were males. A summary of participants' characteristics in terms of demographic data and anthropometric measurements is shown in Table 6.1. The data for individual participants can be found in Appendix E.

Table 6.1: Participants' demographic and anthropometric data

	Mean (SD)
Age (years)	23.75(1.91)
Weight (kg)	69.23(5.19)
Height (cm)	172.04(4.44)
Head height (cm)	17.41(0.99)
Trunk height (cm)	49.93(3.75)
Upper arm length (cm)	34.38(1.73)
Lower arm length (cm)	27.34(2.01)
Hand length (cm)	18.25(0.84)
Hand breadth (cm)	8.40(0.58)
Pelvis width (cm)	31.35(2.18)
Thigh length (cm)	42.63(2.87)
Shank length (cm)	41.28(2.31)
Foot length (cm)	26.82(1.39)

6.2 Experimental Data

6.2.1 Participants' ground reaction force (GRF) data

Table 6.2 shows the measured peak ground reaction forces acted on the right and left foot across all experimental conditions. Raw GRF data are shown in Appendix F.

Table 6.2: Mean (SD) of the peak ground reaction force (GRF) across all experimental conditions

Experimental Conditions	Right Foot						Left Foot					
	Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
0° – 20 kg	56.8 (11.4)	58.4 (18.2)	686.8 (48.7)	74.3 (25.3)	43.5 (13.6)	6.9 (3)	59.1 (10.9)	53.8 (18)	676.9 (56.8)	38.3 (7.3)	35.4 (9.3)	5.3 (1.8)
0° – 30 kg	55 (8.6)	69.3 (13.6)	681.3 (45.7)	70.6 (17.4)	40.4 (8.5)	6.1 (2.5)	56.4 (7.9)	64.5 (24)	672.5 (45.1)	52.7 (16.7)	35.3 (10.9)	5.1 (1.8)
0° – 40 kg	56.8 (10.2)	83.9 (16)	675.1 (43.9)	73.2 (25.2)	42.8 (9.4)	5.4 (2.7)	54.3 (12.2)	76.8 (28.8)	672.6 (42.1)	68.7 (26.9)	33.8 (16.1)	6.1 (2.3)
5°-20kg-up	50.6 (8.2)	135.4 (23.1)	667.8 (45)	65.4 (32.8)	40.5 (11.4)	4.8 (2.5)	60.2 (15.5)	111.2 (14.7)	674.4 (48.2)	41.7 (18.6)	36.8 (10.7)	6.5 (2.3)
5°-30kg-up	56.7 (14)	147.9 (17.9)	673.2 (38.7)	68.4 (17.1)	44.2 (13.5)	7.8 (4.6)	59.5 (7.6)	126.3 (21.5)	653 (18.9)	46.7 (15.5)	37.7 (10.9)	7.8 (3.2)
5°-40kg-up	56.1 (11.3)	171.9 (17.8)	666.5 (65.7)	60.8 (24.8)	49.3 (19.6)	9.2 (5.8)	56.1 (11.5)	145 (31.3)	678.7 (51.9)	44.3 (18.9)	37.3 (10.5)	9.3 (4.3)
5°-20kg-down	72.3 (17.9)	139.8 (15.7)	740 (45.1)	54.6 (14.9)	40.1 (6.5)	7.7 (2.9)	72.6 (19.3)	168.4 (25.8)	716 (58.9)	45.6 (17.2)	39.8 (10.2)	8.6 (4)
5°-30kg-down	69.3 (6.9)	133.6 (28.8)	735.3 (40.5)	68.3 (14.6)	46.5 (6.5)	10.3 (2.8)	67.2 (22)	162.8 (38.6)	715.2 (50.3)	52.2 (22.8)	40 (13.3)	8.3 (5.1)
5°-40kg-down	70.6 (8.6)	146.8 (28.5)	726.2 (73.5)	70.6 (14.3)	43.4 (13.8)	10.8 (5)	69.5 (22.8)	173.3 (47.3)	728.4 (59.7)	68 (57.3)	36.8 (9.2)	9.8 (1.8)
10°-20kg-up	49 (9.9)	196.4 (14.4)	649.9 (37.3)	54.3 (21)	46.8 (7.7)	15.4 (5)	62.9 (14.2)	184.1 (19)	671 (67.9)	52.9 (22.3)	33.3 (13.8)	11.8 (6.4)
10°-30kg-up	47.8 (12)	209.7 (10.2)	650.5 (51.9)	44.6 (24.1)	47.8 (8.5)	16.7 (5.5)	62.9 (10)	191.8 (18.1)	657.8 (66.4)	49.8 (22.4)	26.3 (12.7)	11.6 (4.1)
10°-40kg-up	49.3 (18.2)	229.3 (24.7)	665.3 (79.6)	45.8 (22.1)	45.3 (9.6)	18.4 (5.3)	61.9 (10.5)	205.2 (37.4)	652.7 (69.9)	60.9 (22.5)	23.1 (11.9)	9.8 (5.2)
10°-20kg-down	61.8 (9.8)	174.1 (45.4)	709.1 (54.9)	63 (16)	46.3 (12.3)	11.8 (4.5)	71 (22.5)	199.4 (38)	686.8 (56.9)	47.2 (21.3)	41 (17.9)	15.6 (7.6)
10°-30kg-down	63.6 (18.6)	163.4 (35)	700.3 (53.8)	67.4 (9.2)	49.3 (21.5)	9.8 (4.4)	65.3 (23.6)	204.6 (35.6)	687.6 (64)	43.3 (18.9)	49.1 (13.2)	16.3 (5.3)
10°-40kg-down	72.8 (25.9)	181.1 (52.5)	692.6 (54.7)	58.8 (11.4)	42.7 (12.6)	11.4 (3)	62.2 (26.7)	206.1 (42.7)	689.4 (68.8)	40.3 (25.4)	45.4 (15.9)	16 (9.9)

*Fx,Fy, Fz are in N, and Mx, My, Mz are in Nm.

6.2.2 Major joint angle data

The raw marker data was processed to obtain joint kinematic trajectory for the various joint using the Vicon Nexus software (see Section 4.6.1). The peak joint angle data for major body joints in flexion extension plane are shown in Table 6.3. Raw joint angle data are shown in Appendix G.

6.3 Model 1: Cart Pushing along a Flat Walkway

Raw data for the low back and shoulder joint loading across all experimental situations for two sessions are shown in Appendix H.

6.3.1 Low back joint loading at L5S1

Table 6.4 shows the mean $\pm$ SD of the peak compression and shear forces acting at the L5S1 joint during cart pushing tasks performed under three weight conditions. The amount of the weight transferred significantly affected the peak compression, lateral and anterior-posterior shear forces acting at the L5S1 joint (all $p < 0.001$). The magnitudes of peak forces increased with the increase in the load weight. The magnitude of peak lateral shear force at L5S1 joint was very small compared to the reaction forces in the other two directions. Results of the All-pairwise comparison test (Tukey HSD analysis) showed that the mean of peak lateral shear forces at 20 kg weight condition was different from both 30 kg and 40 kg weight conditions (Table 6.4).

The compression force at the L5S1 joint was higher than the corresponding shear forces. Results of the All-pairwise comparison test showed that the mean of peak compression forces at L5S1 joint were different from one another with respect to three weight conditions (Table 6.4). The shear force at L5S1 joint in the anterior-posterior direction was higher than the respective lateral shear force, but lower than the compression force. Results of the All-pairwise comparison test indicated that the mean of peak shear forces in the anterior-posterior direction at 40 kg weight condition was different from 20 kg and 30 kg weight conditions (Table 6.4).

Table 6.3: The minimum, maximum and mean of peak joint angles (in degrees) for trunk, right upper and lower limbs across all experimental conditions

Experimental Conditions	Trunk Flexion/extension			Right – Shoulder Flexion/extension			Right – Elbow Flexion/extension			Right – Hip Flexion/extension			Right – Knee Flexion/extension			Right – Ankle Flexion/extension		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
0° – 20 kg	-8.3	17.7	4.3	-18.5	32.9	13	30.7	99.1	67.3	-35	29.3	16.3	39.2	63.2	52.8	-15.9	20	7.6
0° – 30 kg	-7.3	18.1	6.5	-20.5	32.2	12	37.1	116.9	69.6	11.1	40.6	23.5	47.1	65.4	56.2	-17.2	20.4	12.8
0° – 40 kg	-10.4	19.7	5.6	-23.2	35.6	7.6	35.7	114.4	65.8	10.9	40.4	24.1	41.7	65.3	56.2	-18.6	20.6	10.6
5°-20kg-up	-4.5	30.0	9.4	-7.2	45.3	25.2	39	119.2	68.1	24.2	49.4	33.3	49.9	73.6	58.2	-24.5	24.7	13.5
5°-30kg-up	-6.8	25.1	14.3	22	65.5	40	39	73.2	62.6	27.1	51.7	36.8	50.9	71.4	57.4	-21.1	26.8	19.4
5°-40kg-up	-5.8	40.4	13.9	-5.5	72.5	36.1	42.3	82.3	61	29.2	53.9	40.2	41.3	70.5	58.7	-25.1	29.5	21.5
5°-20kg-down	-7.0	27.4	7.2	10.7	41	21	44.1	83.5	58.7	11.1	52.7	20.2	19	78.5	57.1	-26.9	28.5	12.7
5°-30kg-down	3.3	38.8	14.3	-172	37	2.6	39.1	97.8	58.4	-4	54.7	21.1	52.2	79.3	65.9	-27.4	30.2	17.3
5°-40kg-down	5.3	55.5	14.8	-9.5	51.6	18	37.1	89.6	55.9	-29.7	54.3	15.2	55.7	75.2	66.7	-25.1	29.4	14.1
10°-20kg-up	6.3	29.8	16.5	16.5	62.9	40.3	55	85.9	68.7	35.4	64.8	44.1	45.1	74.1	58.9	-27.9	35.3	24.8
10°-30kg-up	-8.3	29.7	16.9	-21.2	75.9	37.2	42.7	100	72.9	38.5	68.8	49.5	50.1	77.4	60.6	-48.5	36.8	20.3
10°-40kg-up	-5.2	28.4	15.4	-11.9	85.5	30.4	43.9	131.1	87	45.9	72.2	54.8	55.1	73.9	63.3	-47.3	43	28.2
10°-20kg-down	3.9	36.7	16.8	-5.4	41.2	20.4	38.2	108.4	62.3	-14.8	34.2	18.9	57.9	79.9	69.7	-35.1	26.5	11.2
10°-30kg-down	8.9	32.8	17.6	8.1	58.1	27.5	35.9	70.9	54.3	6.6	38.8	24.1	66.2	87.4	71.9	-38	27.3	12.7
10°-40kg-down	4.5	36.9	16.4	3.4	66.7	25.2	41	84.2	54.3	15.2	41.3	26	60.4	80.6	71.5	-43.1	27.1	9.9

Table 6.4: Mean (SD) of the peak forces acting at the L5S1 joint during pushing task performed on a flat walkway

	20 kg	30 kg	40 kg	p-value
L5S1-ML	43.6(23.2) ^a	63.0(32.7) ^b	77.9(38.9) ^b	< 0.001*
L5S1-PD	863.0(95.1) ^a	1066.2(172.8) ^b	1432.3(252.6) ^c	< 0.001*
L5S1-AP	170.3(58.3) ^a	222.4(87.5) ^a	331.5(104.4) ^b	< 0.001*

Figure 6.1: Peak reaction forces acting at the L5S1 joint in three anatomical directions as a function of load weight

6.3.2 Shoulder joint loading

6.3.2.1 Sternoclavicular (SC) joint loading

The peak forces (mean $\pm$ SD) acting at the sternoclavicular (SC) joint in three anatomical directions during the cart pushing task performed under three weight conditions are shown in Table 6.5. The amount of the load weight had a significant effect on the peak compression, lateral and anterior-posterior shear forces at the SC joint (all $p < 0.001$). The magnitudes of peak forces increased with the increase in the load weight.

Table 6.5: Mean (SD) of the peak forces acting at the sternoclavicular (SC) joint during pushing task performed on a flat walkway

	20 kg	30 kg	40 kg	p-value
RSC – ML	48.2(19.0) ^a	63.5(24.8) ^b	76.0(24.2) ^c	< 0.001*
RSC – IS	52.0(16.7) ^a	74.2(17.0) ^b	111.5(30.7) ^c	< 0.001*
RSC – AP	24.2(8.5) ^a	31.9(13.7) ^b	41.9(13.4) ^c	< 0.001*

The magnitude of the peak lateral shear force at the SC joint was higher than the respective anterior-posterior shear force, but lower than the compression force. Results of the All-pairwise comparison test (Tukey HSD analysis) showed that the mean of peak lateral shear forces at the SC joint were different from one another with respect to three weight conditions (Table 6.5). For the compression force in the inferior-superior direction and shear force in the anterior-posterior direction mean of forces at the SC joint were different from one another with respect to three weight conditions (Table 6.5).

Figure 6.2: Peak reaction forces acting at the sternoclavicular (SC) joint in three anatomical directions as a function of load weight

6.3.2.2 Acromioclavicular (AC) joint loading

The peak forces (mean $\pm$ SD) acting at the acromioclavicular (AC) joint during cart pushing performed under three weight conditions are shown in Table 6.6. The load weight significantly affected the peak compression, lateral and anterior-posterior shear forces at the AC joint (all $p < 0.001$). The magnitudes of peak forces increased with the increase in the load weight from 20 kg to 30 kg to 40 kg.

Table 6.6: Mean (SD) of the peak forces acting at the acromioclavicular (AC) joint during pushing task performed on a flat walkway

	20 kg	30 kg	40 kg	p-value
RAC – ML	204.0(36.7) ^a	308.2(63.0) ^b	404.3(83.8) ^c	< 0.001*
RAC – IS	269.4(62.6) ^a	381.8(88.6) ^b	543.7(112.1) ^c	< 0.001*
RAC – AP	168.0(54.4) ^a	225.7(62.2) ^b	325.4(92.9) ^c	< 0.001*

The lateral shear force at the AC joint was higher than the respective anterior-posterior shear force, but lower than the compression force in the inferior-superior direction. Results of the All-pairwise comparison test (Tukey HSD) showed that the mean of peak lateral shear forces were different from one another with respect to three weight conditions (Table 6.6). The same trend was found for the peak forces acting at the AC joint in the other two directions.

Figure 6.3: Peak reaction forces acting at the acromioclavicular (AC) joint in the three anatomical direction as a function of load weight

6.3.2.3 Glenohumeral (GH) joint loading

During the pushing task on a flat walkway, the amount of the load weight transferred also significantly affected the peak compression, lateral and anterior-posterior shear forces acting at the GH joint (all $p < 0.001$) (Table 6.7). A general trend was found that the magnitudes of peak forces increased with the increase in the load weight.

Table 6.7: Mean (SD) of the peak forces acting at the glenohumeral (GH) joint during pushing task performed on a flat walkway

	20 kg	30 kg	40 kg	p-value
RGH – DIS	344.1(83.0) ^a	479.5(88.9) ^b	681.0(121.3) ^c	< 0.001*
RGH – IS	192.3(83.6) ^a	294.6(136.1) ^a	454.6(150.9) ^b	< 0.001*
RGH – AP	166.2(43.2) ^a	249.3(88.4) ^b	316.2(92.7) ^c	< 0.001*

Figure 6.4: Peak reaction forces acting at the glenohumeral (GH) joint in three anatomical directions as a function of load weight

For the GH joint, among the three anatomical directions, the highest forces were exerted in the distraction direction followed by the inferior-superior and anterior-posterior directions. Results of the All-pairwise comparison test (Tukey HSD analysis) showed that the mean of peak shear forces in the distraction as well as the anterior-posterior direction was different from one another with respect to three weight conditions (Table 6.7). For the compression force in the inferior-superior direction, the mean of peak forces acting at the GH joint at 40 kg weight condition was different from the 20 kg and 30 kg weight conditions (Table 6.7).

6.4 Model 2: Cart Pushing and Pulling along Ramps

6.4.1 Low back joint loading at L5S1

6.4.1.1 Main effects

A general trend in the data indicates that the peak compression and shear forces acting at the L5S1 joint increased with the increase in the load weights and the ramp heights (Figure 6.5). Among the two directions of force application, higher joint loading was observed during uphill pushing than downhill pulling. Statistically, the main effect of load weight, walkway gradient, and direction of force exertion on the peak L5S1 compression and shear forces in the anterior-posterior (AP) direction was significant (all $p \leq 0.01$). The shear force in the lateral (ML) direction at the L5S1 joint was not affected by the walkway gradient ($p = 0.52$), but was

significantly affected by load weight and direction of force application ($p < 0.01$). The magnitude of the lateral shear force at the L5S1 joint was very small compared to the reaction forces in the other two directions (< 150 N in all situations).

Figure 6.5: Main effect plots for the loading of the L5S1 joint in three directions ((a) L5S1-ML; (b) L5S1-PD; (c) L5S1-AP) by the walkway gradient, load weight, and direction of force application

6.4.1.2 Two-way interaction effects

The interaction effect between the walkway gradient and load weight was significant for the peak shear force in the AP direction at the L5S1 joint ($p = 0.04$). This interaction effect was ordinal, suggesting that at the 40 kg weight condition, increase in the walkway gradient caused a relatively higher increase in the peak shear force in the AP direction than at 20 and 30 kg weight conditions (Figure 6.6 (c)). The interaction effect between the walkway gradient and direction of force exertion was significant for the peak compression and shear forces acting at the L5S1 joint (all $p \leq 0.01$). A

disordinal interaction effect was observed, meaning that with the increase in the walkway gradient from 5° to 10°, compression and shear forces acting at the L5S1 joint increased during uphill pushing. During downhill pulling, these forces decreased with the increase in the walkway gradient from 5° to 10°. An ordinal interaction effect was also observed between load weight and direction of force application for the loading of the L5S1 joint in the three directions (all $p \leq 0.01$). During uphill pushing, an increase in the weight of the cart caused a relatively higher increase in the 3D loading of the L5S1 joint than downhill pulling.

Figure 6.6: Two-way interaction plots for the loading of the L5S1 joint in three directions: (a) L5S1-ML; (b) L5S1-PD; (c) L5S1-AP

6.4.1.3 Three-way interaction effect and Tukey HSD analysis

The dataset was unstacked by the gradient (5° and 10°) to facilitate the interpretation of the three-way interaction effect (Figure 6.7). Three-way interaction effect between walkway gradient, load weight, and direction of force application was significant for the peak compression and anterior-posterior shear forces acting at the L5S1 joint (both $p < 0.01$) (Figures 6.8 – 6.10).

At 5° gradient increase in the load weight increased the peak compression, lateral and anterior-posterior shear forces during uphill pushing as well as downhill pulling. Results of the All-pairwise comparison test showed that the mean of peak compression, lateral and anterior-posterior shear forces at 40 kg weight condition was different from 20 kg weight condition during uphill pushing and downhill pulling. During downhill pulling, the mean of peak compression forces at 40 kg weight was also different from 30 kg weight condition. A comparison between the directions of force application indicates that the mean of peak lateral forces during uphill pushing at 40 kg weight was higher than downhill pulling.

On the 10° ramp, during uphill pushing, the mean of peak compression and anterior-posterior shear forces at 20, 30, and 40 kg weight conditions were different from one another, while the mean of peak lateral forces at 40 kg weight was different from 20 kg and 30 kg weight. No significant difference was found between the three weight conditions during downhill pulling. A between direction of force application comparison indicates that the mean of peak compression, lateral, anterior-posterior shear forces during uphill pushing at 30 kg and 40 kg weight conditions was higher than downhill pulling. Additionally, the mean of peak anterior-posterior shear forces during uphill pushing at 20 kg weight was higher than downhill pulling.

A between gradient comparison indicates that the mean of peak compression and anterior-posterior shear forces during uphill pushing under 30 kg and 40 kg load weight conditions were higher along the 10° ramp than the 5° ramp.

Figure 6.7: Three-way interaction plots for the loading of the L5S1 joint unstacked by the walkway gradient (degree) factor

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A *	B	C	A×B	A×C	B×C	A×B×C	
62 (19)	59 (18)	83 (27)	81 (20)	126 (18)	98 (28)	78 (20)	55 (14)	88 (32)	64 (19)	139 (27)	75 (18)	0.52	<0.01	<0.01	0.18	<0.01	<0.01	0.42	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.8: Peak force acting at the L5S1 joint in the medio-lateral direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A *	B	C	A×B	A×C	B×C	A×B×C	
1160 (221)	956 (187)	1499 (287)	1416 (373)	1899 (339)	2204 (866)	1469 (302)	1019 (256)	2420 (354)	1027 (102)	3222 (378)	1189 (548)	0.01	<0.01	<0.01	0.74	<0.01	0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.9: Peak force acting at the L5S1 joint in the compression (proximal-distal) direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
260 (61)	187 (43)	343 (66)	278 (75)	422 (91)	375 (146)	329 (68)	196 (53)	553 (104)	218 (21)	806 (121)	238 (112)	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.10: Peak force acting at the L5S1 joint in the anterior-posterior direction during uphill pushing and downhill pulling

6.4.2 Shoulder joint loading at sternoclavicular joint

6.4.2.1 Main effects

Generally, the peak compression and shear forces acting at the sternoclavicular (SC) joint increased with the load weight, walkway gradient, and direction of force application (Figure 6.11). Statistically, the main effect of load weight, walkway gradient, and direction of force exertion on the peak SC joint compression and shear forces was significant (all $p < 0.01$). The joint loading increased with the increase in the load weight and the walkway gradient. The main effect of direction of force application was also significant, where larger joint forces were observed during uphill pushing than downhill pulling.

Figure 6.11: Main effect plots for the loading of the sternoclavicular (SC) joint in three directions ((a) RSC-ML; (b) RSC-IS; (c) RSC-AP) by the walkway gradient, load weight, and direction of force application

Overall, the magnitude of shear force at the SC joint in the anterior-posterior direction was very negligible (< 65 N in all situations) compared to the peak forces in the other two directions.

6.4.2.2 Two-way interaction effects

Two-way interaction effects are shown in Figure 6.12. The interaction effect of load weight by walkway gradient was significant for the peak compression and shear forces acting at the SC joint ($p \leq 0.01$). The loading at 10° walkway gradient combined with 40 kg load weight condition was higher than all the weight conditions at 5° walkway gradient. The disordinal interaction between walkway gradient and direction of force application was significant for the peak forces acting at the SC joint ($p < 0.01$). With the increase in the walkway gradient from 5° to 10°, the peak forces in three directions increased during uphill pushing, whereas during downhill pulling, these forces decreased with the increase in the walkway gradient from 5° to 10°. A significant load weight by direction of force application interaction effect was observed for the loading of the SC joint in the three directions ($p < 0.05$). During uphill pushing, increase in the load weight caused a relatively higher increase in the lateral and compression forces at the SC joint than downhill pulling. A reverse pattern was observed in the anterior-posterior force direction, where increase in the load weight caused a relatively higher increase in the AP shear forces acting at the SC joint during downhill pulling than uphill pushing.

Figure 6.12: Two-way interaction plots for the loading of the sternoclavicular (SC) joint in three directions: (a) RSC-ML; (b) RSC-PD; (c) RSC-AP

6.4.2.3 Three-way interaction effect and Tukey HSD analysis

The dataset was unstacked by the walkway gradient (5° and 10°) to facilitate the three-way interaction effect interpretation (Figure 6.13). A three-way interaction effect between walkway gradient, load weight, and direction of force exertion was significant for the peak forces acting at the SC joint in the three directions ($p < 0.01$) (Figures 6.14 – 6.16).

At the walkway gradient of 5° , increase in the load weight increased the peak compression, lateral and anterior-posterior shear forces during downhill pulling. During uphill pushing, increase in the load weight increased the peak compression and anterior-posterior shear forces. Results of the All-pairwise comparison test showed that during downhill pulling, the mean of peak forces in three directions at the 40 kg weight condition was different from the 30

kg weight condition. In addition to that, the 30 kg weight condition caused larger forces in the lateral and AP shear directions than the 20 kg weight condition during downhill pulling. The mean of peak compression and AP shear forces at 40 kg weight condition was different from 20 kg weight condition during downhill pulling as well as uphill pushing. A comparison between the direction of force exertion indicates that the mean of peak lateral forces during downhill pulling at 30 kg and 40 kg weight conditions were higher than uphill pushing. Additionally, the mean of peak shear forces in the anterior-posterior direction at the 40 kg weight condition was larger than uphill pushing.

On the 10° ramp, during uphill pushing, the mean of peak lateral forces at 30 kg and 40 kg weight conditions was different from the 20 kg weight condition. A coherent trend was observed for the mean of peak compression forces which increased with the increase in the load weight during uphill pushing. The mean of peak shear forces in the anterior-posterior direction at the 40 kg weight condition was larger than the 20 kg and 30 kg weight conditions during uphill pushing. No significant difference was observed between the three weight conditions during downhill pulling. A between direction of force application comparison shows that the mean of peak forces in the three directions during uphill pushing at 30 kg and 40 kg weight conditions was larger than downhill pulling.

A between gradient comparison shows that the mean of peak compression, lateral and anterior-posterior shear forces during pushing the load weight of 40 kg uphill was higher at the 10° ramp than the 5° ramp condition.

Figure 6.13: Three-way interaction plots for the loading of the sternoclavicular (SC) joint unstacked by the walkway gradient (degree) factor

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
72 (15)	70 (29)	78 (37)	115 (38)	82 (31)	171 (34)	83 (38)	65 (21)	191 (45)	79 (25)	211 (43)	71 (32)	<0.01	<0.01	<0.01	0.01	<0.01	0.04	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.14: Peak force acting at the sternoclavicular (SC) joint in the medio-lateral direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
70 (20)	82 (17)	86 (18)	90 (26)	139 (21)	133 (35)	101 (25)	75 (17)	146 (21)	93 (29)	200 (25)	88 (26)	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.15: Peak force acting at the sternoclavicular (SC) joint in the inferior-superior direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A *	B	C	A×B	A×C	B×C	A×B×C	
27	29	38	39	42	61	48	29	48	38	61	45	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
(5)	(7)	(8)	(11)	(8)	(10)	(7)	(8)	(11)	(7)	(13)	(7)								

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.16: Peak force acting at the sternoclavicular (SC) joint in the anterior-posterior direction during uphill pushing and downhill pulling

6.4.3 Shoulder joint loading at acromioclavicular joint

6.4.3.1 Main effects

A general trend in the data indicate that the peak forces in three directions acting at the acromioclavicular (AC) joint increased with the increase in the load weight and walkway gradient (Figure 6.17). The comparison between two directions of force application shows that uphill pushing caused larger joint forces than downhill pulling. Statistically, the main effect of load weight, walkway gradient, and direction of force exertion on the peak AC joint forces in three directions was significant (all $p < 0.01$).

Figure 6.17: Main effect plots for the loading of the acromioclavicular (AC) joint in three directions ((a) RAC-ML; (b) RAC-IS; (c) RAC-AP) by the walkway gradient, load weight, and direction of force application

6.4.3.2 Two-way interaction effects

The interaction effect of the walkway gradient by load weight was significant for the peak shear force in the anterior-posterior direction at the AC joint ($p = 0.01$). The

interaction effect was ordinal, indicating that the increase in the walkway gradient at 40 kg weight caused a relatively higher increase in the peak AP shear force than at 20 kg and 30 kg weight conditions (Figure 6.18 (c)). A disordinal interaction effect between walkway gradient and direction of force application was observed for the peak forces in three directions ($p < 0.01$). With the increase in the walkway gradient from 5° to 10° , the peak forces in three directions increased during uphill pushing, whereas during downhill pulling these forces decreased with the increase in the walkway gradient from 5° to 10° . The effect of load weight and direction of force exertion was ordinal and significant for the peak forces in three directions ($p < 0.01$). It was observed that the increase in the load weight caused a relatively higher increase in the loading at the AC joint during uphill pushing than downhill pulling activities.

Figure 6.18: Two-way interaction plots for the loading of the acromioclavicular (AC) joint in three directions: (a) RAC-ML; (b) RAC-IS; (c) RAC-AP

6.4.3.3 Three-way interaction effect

A three-way interaction effect of walkway gradient by load weight by direction of force exertion was significant for the peak forces acting at the AC joint in three directions ($p < 0.01$) (Figures 6.20 – 6.22).

As shown in Figure 6.19 (a) (c) (e), at the ramp of 5°, increase in the load weight increased the peak compression and shear forces during uphill pushing as well as downhill pulling. Results of the All-pairwise comparison test indicated that the mean of peak forces in three directions at 40 kg weight condition was different from 20 kg weight condition during uphill pushing and downhill pulling. In addition, the mean of peak compression force in the inferior-superior direction at 40 kg weight condition was different from 30 kg weight condition during uphill pushing.

As can be seen in Figure 6.19 (b) (d) (f), at the ramp of 10°, the mean of peak forces in three directions increased with the increase in the load weight during uphill pushing activities. Results of the All-pairwise comparison test indicated that the mean of peak compression, lateral and anterior-posterior shear forces increased with the corresponding three weight conditions. No significant difference was observed between the three weight conditions during downhill pulling. A comparison between directions of force exertion showed that the mean of peak forces acting at the AC joint in three directions during uphill pushing at 30 kg and 40 kg weight conditions was higher than downhill pulling. This direction difference was also observed for the mean of peak compression force in the inferior-superior direction at 20 kg weight condition.

A between walkway gradient comparison showed that the mean of peak forces in three directions during uphill pushing at 30 kg and 40 kg weight conditions was higher at the ramp of 10° than 5°. The same trend was also observed at 20 kg weight condition for the mean of peak forces in lateral and compression forces.

Figure 6.19: Three-way interaction plots for the loading of the acromioclavicular (AC) joint unstacked by the walkway gradient (degree) factor

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A *	B	C	A×B	A×C	B×C	A×B×C	
236 (67)	265 (72)	336 (133)	381 (156)	454 (147)	471 (190)	401 (143)	278 (212)	558 (204)	350 (92)	910 (101)	366 (117)	<0.01	<0.01	<0.01	0.07	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.20: Peak force acting at the acromioclavicular (AC) joint in the medio-lateral direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
298 (77)	273 (79)	420 (90)	422 (195)	626 (189)	565 (297)	515 (133)	292 (227)	784 (198)	330 (108)	1078 (73)	373 (175)	<0.01	<0.01	<0.01	0.95	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.21: Peak force acting at the acromioclavicular (AC) joint in the inferior-superior direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
202 (63)	192 (82)	249 (73)	279 (84)	360 (78)	338 (106)	286 (114)	202 (92)	479 (104)	199 (68)	727 (40)	227 (78)	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.22: Peak force acting at the acromioclavicular (AC) joint in the anterior-posterior direction during uphill pushing and downhill pulling

6.4.4 Shoulder joint loading at glenohumeral joint

6.4.4.1 Main effects

In general, as shown in Figure 6.23, the peak compression and shear forces acting at the glenohumeral (GH) joint increased with the increase in the load weight. Compared to downhill pulling, uphill pushing caused higher forces in three directions. Statistically, the main effect of walkway gradient, load weight, and direction of force application was observed in the joint forces acting at the GH joint in three directions (all $p < 0.01$). The magnitude of distraction shear force at the GH joint was larger than the compression force in the inferior-superior direction and shear force in the anterior-posterior direction.

Figure 6.23: Main effect plots for the loading of the glenohumeral (GH) joint in three directions ((a) RGH-DIS; (b) RGH-IS; (c) RGH-AP) by the walkway gradient, load weight, and direction of force application

6.4.4.2 Two-way interaction effects

A disordinal interaction effect of walkway gradient by load weight was observed for the peak shear force in the anterior-posterior direction at the GH joint ($p = 0.04$). As can be seen in Figure 6.24 (c), the increase in the load weight along the walkway gradient of 10° caused a relatively higher increase in the peak AP shear forces than the gradient of 5° . The interaction effect between walkway gradient and direction of force exertion was evident for the peak forces in three directions (all $p < 0.01$). It was observed that with the increase of walkway gradient from 5° to 10° , peak forces in three directions increased during uphill pushing, whereas during downhill pulling, these forces decreased with the increase of walkway gradient from 5° to 10° . Finally, an ordinal interaction effect between load weight and direction of force application was found for the peak forces at the GH joint in three directions (all $p < 0.01$). Corresponding to the increase in the load weight, a relatively higher increase was observed for the 3D loading of GH joint during uphill pushing than downhill pulling.

Figure 6.24: Two-way interaction plots for the loading of the glenohumeral (GH) joint in three directions: (a) RGH-DIS; (b) RGH-IS; (c) RGH-AP

6.4.4.3 Three-way interaction effect and Tukey HSD analysis

The peak compression and shear forces acting at the GH joint was also significantly affected by the three-way interaction effect between walkway gradient, load weight, and direction of force application (all $p < 0.05$) (Figure 6.26 – 6.28).

Figure 6.25 (a) (c) (e) shows the three-way interaction effect depending on the walkway gradient of 5° . Corresponding to the increase in the load weight, the peak compression and shear forces increased during uphill pushing as well as downhill pulling. Results of the All-pairwise comparison test indicated that the mean of peak forces in three directions at 40 kg weight condition was larger than 20 kg weight during uphill pushing and downhill pulling. During uphill pushing, the mean of peak distraction and anterior-posterior shear forces at the 30 kg weight condition was different from 20 kg weight condition. During the same direction of force application, the mean of peak distraction and compression (inferior-superior direction) forces at 40 kg weight condition was different from the 30 kg weight condition. On the other hand, during downhill pulling, the mean of peak distraction and compression forces at 30 kg weight condition was different from the 20 kg weight condition. Moreover, the mean of peak shear force in anterior-posterior direction at 40 kg weight condition was also different from the 30 kg weight condition during downhill pulling.

Figure 6.25 (b) (d) (f) shows the three-way interaction effect depending on the walkway gradient of 10° . A coherent trend was observed for the peak compression and shear forces during uphill pushing. The 3D loading of the GH joint increased with the increase in the load weight. A comparison between the directions of force exertion shows that the mean of peak forces acting at the GH joint in three directions during uphill pushing at 30 kg and 40 kg weight conditions was higher than downhill pulling. For the mean of peak compression force in the inferior-superior direction, the uphill pushing activities under the 20 kg weight condition caused larger forces than downhill pulling.

A between walkway gradient comparison shows that during uphill pushing, the 10° ramp caused larger joint forces in three directions than the 5° ramp at 30 kg and 40 kg weight conditions. Under the same conditions, a similar trend was observed for the peak distraction force and compression forces at the 20 kg weight condition.

Figure 6.25: Three-way interaction plots for the loading of the glenohumeral (GH) joint unstacked by the walkway gradient (degree) factor

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A *	B	C	A×B	A×C	B×C	A×B×C	
447 (132)	508 (153)	650 (167)	712 (168)	868 (192)	780 (168)	709 (97)	526 (176)	1025 (152)	628 (126)	1357 (145)	702 (204)	<0.01	<0.01	<0.01	0.44	<0.01	<0.01	0.02	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.26: Peak force acting at the glenohumeral (GH) joint in the distraction direction during uphill pushing and downhill pulling

5°						10°						p-value						
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg								
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C
219 (68)	213 (67)	330 (143)	363 (143)	530 (238)	367 (199)	459 (122)	187 (77)	657 (65)	207 (70)	858 (123)	221 (111)	<0.01	<0.01	<0.01	0.88	<0.01	<0.01	0.03

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.27: Peak force acting at the glenohumeral (GH) joint in the inferior-superior direction during uphill pushing and downhill pulling

5°						10°						p-value							
20 kg		30 kg		40 kg		20 kg		30 kg		40 kg									
1	2	1	2	1	2	1	2	1	2	1	2	A*	B	C	A×B	A×C	B×C	A×B×C	
186 (41)	175 (41)	278 (75)	234 (62)	349 (94)	357 (119)	261 (47)	202 (41)	458 (85)	249 (46)	618 (109)	326 (120)	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	

* A= walkway gradient; B= load weight; C= direction of force application

Figure 6.28: Peak force acting at the glenohumeral (GH) joint in the anterior-posterior direction during uphill pushing and downhill pulling

CHAPTER 7: DISCUSSION

The current study was designed to quantify the effects of load weight, walkway gradient, and direction of force application on musculoskeletal loading during pushing and pulling a cart on a wooden walkway. The musculoskeletal loading was characterized by the peak joint reaction forces acting at the L5S1 joint of the low back and three shoulder joints (e.g., sternoclavicular, acromioclavicular, and glenohumeral joint) in three anatomical directions.

The discussion of the findings of this study is divided into four major sections. In the first section, the effects of load weight, walkway gradient, and direction of force application on low back loading are discussed. The second section focuses on the effects of the aforementioned factors on shoulder joint loading. In the third section, limitations of the current study are presented and finally, based on the findings of the present study, some practical implications are formulated in the fourth section.

7.1 Low Back Loading

7.1.1 Effect of load weight

The magnitude of peak shear forces in the lateral direction at the L5S1 joint was very small (< 150 N) compared to the reaction forces in the anterior-posterior and proximal-distal directions. The reaction forces in these two directions increased with the increase in the magnitude of load weight. This observation is in agreement with a number of previous studies. Jäger et al. (2007) and Laursen and Schibye (2002) reported similar effect of load mass on the resultant lumbar-disc compression forces. Hoozemans (2004) also concluded that load weight had a significant effect on the mechanical load at the low back in terms of peak compression forces and net moments.

Although the overall trends observed in the behavior of shear and compression forces at L5S1 joint in this study are similar with the previous studies, the actual magnitudes of the reaction forces found in this study are relatively higher than the previous studies. Laursen and Schibye (2002) reported the peak compression and anterior-posterior shear forces of 751 and 952 N, and 43 and 80 N at the L4L5 joint for load weights of 25 kg and 50 kg, respectively. In

the present study, for the load weights of 30 and 40 kg, the peak compression forces were 863 and 1432 N and the peak anterior-posterior shear forces were 170 and 331 N, respectively. Another study, Jäger et al. (2007) reported the peak compression forces of 1200 N and 1500 N during a cart pushing tasks performed along a 5° inclined surface for the cart weights (combined weight of cart and load) of 40 and 65 kg, respectively. In the present study the weight of the cart was 14 kg, therefore, for 30 and 40 kg weight conditions the cart weights (combined weight of cart and load) was approximately 45 and 55 kg, respectively. For these weights, during the pushing tasks performed along a 5° gradient, the peak compression forces at L5S1 were 1500 N and 1900 N, respectively. The most likely explanation for the higher low back compression and/or anterior-posterior shear forces observed in this study is the difference in the biomechanical models. In the studies of Jäger et al. (2007) and Laursen and Schibye (2002), low back loading was computed using a single equivalent muscle model. This type of simple biomechanical models employs either one back muscle or one abdominal muscle to compute the joint loading and neglects the coactivation of the other back and trunk muscles. The coactivation of trunk muscles has been found to substantially increase the mechanical loads such as compression and shear forces on the lumbar spine (Hoozemans, et al., 2004; Garg & Kapellusch, 2009). The present study used a more comprehensive biomechanical model that consider the muscle co-contraction and minimum/maximum muscle recruitment strategy to calculate the joint reaction forces acting at the low back joint . On average, compressive and anterior-posterior shear forces estimated by the model used in this study were 34% and 75% higher than the previous studies. These percentage values are to some extent in agreement with the finding of Garg & Kapellusch (2009), who argued that using a single equivalent muscle model might underestimate spine compression forces by as much as 45% and shear forces by as much as 70% (Garg & Kapellusch, 2009).

7.1.2 Effect of walkway gradient

It was found that the peak compression and anterior-posterior shear forces acting at the L5S1 joint increased with the increase of walkway inclination. Only one previous study by Jäger et al. (2007) reported mechanical load on the low back during pushing and pulling along an inclined floor. The results of the present study concerning the effect of walkway gradient are in agreement with the findings of Jäger et al. (2007), who also found that the lumbar load in terms

of L5S1 compression increased with the increase in the floor gradient. At 0° and 5° inclined surfaces, L5S1 peak compression forces of 800 and 900 N and 1200 and 1500 N were reported by Jäger et al. (2007) for of the cart weights (combined weight of cart and load) of 45 and 65 kg, respectively. In the present study, for the similar conditions, the peak compression of 1066 and 1432 N, and 1500 and 1900 N, were observed. A higher loading found the present study is mainly due to co-contraction of the trunk muscles as explained in the last paragraph. In a different type of study, Bennett et al. (2008) found that uphill pushing and downhill pulling efforts resulted in higher hand forces compared to level pushing, indicating higher demands on the musculoskeletal system during pushing/pulling exertions performed over inclined surfaces.

7.1.3 Effect of direction of force application

One of the main finding of this study was that uphill pushing caused larger spinal forces than downhill pulling activities. The results indicated that the low back joint loading was considerably affected by the direction of force application along the ramps. The largest peak compression force of 3222 N at the L5S1 joint was observed during uphill pushing on a 10° ramp for the load weight of 40 kg. This force was 2000 N more than the corresponding peak compression force during downhill pulling. The largest peak anterior-posterior shear force of 806 N was found when pushing the 40 kg weight upward on the 10° ramp. This force was decreased to 238 N during downhill pulling under the same weight and gradient conditions. On average, uphill pushing operations imposed up to 26.4% and 38.3% greater peak compression and anterior-posterior shear forces compared to downhill pulling. No previous study has reported the effect of direction of force application along the inclined surface on the lumbar load. (Bennett, et al., 2008) reported that peak hand forces during uphill efforts were 31-40% higher than peak downhill efforts. Jäger et al. (2007) reported that pushing and pulling of the large containers lead to the highest lumbar load in cases of superimposition of considerable trolley mass and considerable floor gradient. This is to some extent in agreement with the current study that uphill pushing of considerable load weight (40 kg weight) along the considerable floor gradient (10° ramp) constantly generated the higher low back loading than any other combinations of the task factors (load weight, walkway gradient, and direction of force application). However, the effect of direction of force application along the inclined surface on the lumbar load was not reported in the study of Jäger et al. (2007).

Higher load levels during uphill pushing than the downhill pulling could be explained by two factors. The first explanation is the difference in overall technique used between these two types of exertions. During uphill pushing in order to improve stability and overcome the downward effect of load gravity, the participants exerted more efforts to control the load weight. In this context, the cart handle was kept high and farther away from the trunk and shoulder joints, resulting in a larger lever arm of the joints and higher musculoskeletal loading. Contrarily, during downhill pulling, the cart handle was kept close to trunk and shoulder joints causing a smaller lever arm and thus eliciting lower joint loading. The second explanation for the higher peak forces at the L5S1 joint during uphill pushing was the forward flexed trunk postures used during these exertions. During uphill pushing along the ramp higher trunk inclination required substantial co-activations of the trunk flexors to stabilize the low back joints. Most of these oblique flexor muscles have a large horizontal muscle fiber orientation and limited cross-sectional area and therefore generate significant shear and compression forces at the L5S1 joint (Knapik & Marras, 2009).

7.1.4 Risk of low back injury

In the present study, the peak compression forces of 2420 N and 3222 N were observed for 30 kg and 40 kg weight conditions, respectively, when pushing the cart uphill along the 10° ramp. These values are below the recommended NIOSH limit of 3400 N (NIOSH, 1981) but are closer to/higher than the limit of 2500 N, which was chosen as the criterion for evaluating low back disc compression during trolley maneuvers by Jäger et al. (2007). Regarding the shear forces, a tolerance limit of approximately 500 N was suggested by McGill (2007). The peak shear forces in the lateral direction observed in this study were negligible (140 N) compared to the recommended criterion. However, the shear forces in the anterior-posterior (AP) direction were found to be higher than 500 N during uphill pushing along the 10° ramp at 30 kg and 40 kg load weight conditions. Thus, some risk of low back injury, mainly due to increased loading in the anterior-posterior shear direction, is associated with uphill pushing exertions performed along 10° ramp for the load weight of 30 kg (combined weight of 44 kg) and higher. A similar conclusion was made by Knapik and Marras (2009) for pushing exertions based on the identical trend in the compression and shear forces observed during pushing exertions.

7.2 Shoulder Loading

7.2.1 Effects of load, gradient, and direction of force application

In this study, the mechanical load in terms of joint forces acting at the three joints of the shoulder complex was quantified. The variations in walkway gradient as well as the load weight and the direction of force application along the ramp significantly affected the forces acting at the sternoclavicular (SC), acromioclavicular (AC) and glenohumeral (GH) joints.

Similar to the trend found for the low back loading, the main findings of shoulder joint loading are as following: as the load weight increased, so did the resultant peak forces in three directions acting at the shoulder joints; the shoulder loading increased with an increase of gradient; uphill pushing generated larger forces around the shoulder joints than downhill pulling. The findings of effect of load weight on shoulder joint loading are partially in agreement with studies of Schibye et al. (2001) and Laursen and Schibye (2002). Schibye et al. (2001) found that shoulder loading in terms of torques were larger during pushing and pulling of 50 kg of waste container compared to 25 kg waste container. Laursen and Schibye (2002) reported that there was a significant increase in shoulder torque magnitude when container weight was increased. The effects of walkway gradient and direction of force application on the mechanical load of shoulder complex joints have not been explored before in the literature.

A few studies have reported mechanical load on the shoulder joint during pushing and pulling, in terms of net moments (De Looze, et al., 2000; Van der Woude, et al., 1995; Abel & Frank, 1991). However, no previous study have reported the loading of the three shoulder joints, e.g. SC, AC, and GH joints in three anatomical directions during pushing pulling exertions. The study of Hoozemans et al. (2004) is the only available study that reported compression forces in the inferior-superior direction at the GH joint. In this study, the authors have reported that the compression forces at the GH joint were significantly affected by the load weight and the direction of force application. The authors of this study have also presented generalized estimating equations (GEE) for quantifying GH loading during pushing/pulling exertions. Based on this equation for the load weight of 40 kg along a horizontal surface, a compression force of 482 N was estimated at the GH joint. This value is close to the peak compression force of 455 N estimated in the present study.

7.2.2 Comparison among shoulder complex joints

The results showed that the largest reaction forces were acted upon at the GH joint, while the forces activated around the SC joint were the smallest. This can be explained by the anatomical structure of these joints in the shoulder complex (see Section 2.3). Compared to the SC and AC joints, the GH joint has the largest range of motion (RoM) and uses more muscle forces for stabilization during the motion. The co-contraction of the muscle around the GH joint contributes to the higher reaction forces at this joint. Contrastingly, the RoM of the SC joint is rather small and there is hardly any active muscle tissue surrounding this joint to exert forces, and consequently, forces due to muscle co-contraction are negligible (van Drongelen, van der Woude, & Veeger, 2011). A similar behavior of shoulder joints, i.e. relatively higher loading for the GH joint compared to the other two shoulder joints (SC and AC) is also reported by van Drongelen et al. (2011). During wheelchair-related propulsion activities, van Drongelen et al. (2011) found that the reaction forces on the SC and AC joints were only one third of those on the GH joint. However, a comparison of the resultant shoulder joint forces between the two studies is not possible because of the totally different nature of the tasks studied. In the context of the current study, the largest shoulder joint forces were observed when pushing the load weight of 40 kg uphill along a gradient of 10°. The peak forces in three directions (distraction, inferior-superior, and anterior-posterior) at the GH joint were as high as 1357 N, 858 N, and 618 N, respectively. The peak forces found at the AC joint were: 910 N, 1078 N, and 727 N, respectively, for lateral, inferior-superior, and anterior-posterior shear forces. The corresponding forces at the SC joint were 211 N, 200 N, and 61 N, respectively. Although the loading of the SC joint is comparatively lower than the GH joint, the force acting at the AC joint are quite high and are comparable with the GH joint. In the existing literature the focus has always been on the loading at the GH joint. The results of the present study show that, in addition to the GH joint, AC joint is also loaded to higher levels during the uphill pushing exertions. The higher loading of the AC joint observed in this study may explain musculoskeletal problems reported for this joint by van Drongelen et al. (2011) and Buttaci et al. (2004) during pushing exertions.

7.2.3 Risk of shoulder injury

Shoulder tendinitis, rotator cuff pain, and nonspecific shoulder pain are the common work-related shoulder complex pathologies. A general pathomechanism for most of these pain syndromes is the inflammation of muscle tendons caused by their impingement in the bony structures in the shoulder region. The tendons to the rotator cuff muscles and the long head of the biceps brachii are common sites for inflammation in the shoulder. During the uphill pushing activities along a ramp, the shoulder joint was flexed combined with abduction, and arm rotation. Such posture of shoulder demands a relative higher loading for the AC and GH joints, mainly in the inferior-superior and distraction directions. The forces acting in these anatomical directions may cause impingement of the rotator cuff muscles (supraspinatus, infraspinatus, teres minor, and subscapularis muscles) (Silverstein, et al., 1998) during such exertion. This can also accelerate the degeneration of these muscles because of the impaired circulation caused by the impingement. As a consequence, the uphill pushing activities along an inclined walkway may impose a detrimental impact in the shoulder region.

Little is known about the safe loading limits for the shoulder joints. A tolerance limit of 500 N, which is same as the tolerance limit for the low back shear forces is used in this study to evaluate the risk of shoulder injuries during pushing/pulling exertions. In the following situations the loading of the shoulder joints exceeded 500 N:

- (1) For the AC joint in the lateral and AP directions: while pushing the load weight of 30 kg and 40 kg uphill along a walkway gradient of 10°; (four situations)
- (2) For the GH joint in distraction (lateral) direction: while pushing the load weight of 30 kg and 40 kg uphill along the two gradients (5° and 10°) of the walkway. (four situations)

When compared with L5S1 joint, only in two of the above eight situations, a risk of low back injury due to higher anterior-posterior shear loading was identified. Clearly, shoulder joint is found to be at a relatively higher risk of injuries during the uphill pushing activities than the low back. However, this claim was based on a tolerance limit of 500 N. Future studies evaluating accurate tolerance limits for the shoulder joints are needed to more accurately understand the risk of injuries during occupational exertions.

7.3 Study Limitations

There are a few limitations of this study that need to be acknowledged. First, the findings of this study are a function of the experimental conditions investigated. It should be noted that during uphill pushing hand forces were directed away from the body, while during downhill pulling the hand forces were directed toward the body. In both cases, the participants walked forward along a ramped wooden walkway. At workplaces the workers operate on different types of surfaces, which may be different from the wooden surface used in this study. These surfaces may provide different levels of resistance against the movement of the cart and may affect the directions and magnitudes of the pushing /pulling forces and the overall technique and working postures differently. Moreover, the cart used in this study is one of the most frequently used carts at workplaces. Other carts with different dimensions are also used at various other workplaces. Different cart dimensions, especially handle height and physical dimensions of the cart, with respect to its center of mass could affect direction of the forces as well as the posture and movement, and therefore, the mechanical load on the musculoskeletal system (Hoozemans, et al., 2004).

Second, only sustained pushing and pulling phases were investigated, while no attention was paid to the initial phase of accelerating objects and the ending phase of decelerating the object and bringing it to a standstill (Bennett, et al., 2008; van Dieen & Kingma, 1999). These motion phases could result in different musculoskeletal loading. In a study performed by Bennett et al. (2008), it was found that during uphill pushing, initial phase of accelerating objects was the most taxing, whereas during downhill pulling, ending phase was found to impose the greatest stress on the musculoskeletal system.

Third, the effects of load weight, walkway gradient, and direction of force application along ramps are specific to the population used in the current study. Participation was voluntary and the participant pool was limited to university-aged students with little to no manual materials handling experience.

7.4 Practical Implication

In order to prevent work-related MSD, it is important to know the exact quantitative load acting on the musculoskeletal system during occupational exertions. This information is

necessary for performing potential risk assessment and for developing appropriate interventions strategies. Although the results of this study demonstrate that low back and shoulder joints loading during pushing and pulling exertions is affected by a number of task factors and their interaction with each other, problematic loading was observed only at a few instances. For the low back, anterior-posterior (AP) shear loads at L5S1 joint was found to be higher than the accepted safe limit. Among the shoulder joints, the highest level of loading was observed for the AC joint in the inferior-superior (IS) direction and for the GH joint in the distraction (DIS) direction. Among the various experimental conditions evaluated in this study, pushing tasks performed at a walkway gradient of 10° at 30 and 40 kg weight conditions were found to be detrimental for the aforementioned joints.

Based on the findings of this study the following regression equations are developed for quantifying loading of the key low back and shoulder joints during uphill pushing exertions (Appendix L). These equations can be used to quantify the effect of tasks factors such as walkway gradient and load weight on the loading of the key low back and shoulder joints during uphill pushing exertions. By comparing the quantitative loading with the safe acceptable loading limits risk for the low back and shoulder MSD injuries during cart pushing tasks performed on inclined surfaces could be identified.

$$L5S1-AP = 57.6 - 15.2 \text{ Degree} + 5.45 \text{ Weight} + 1.58 \text{ Degree*Weight}$$

$$RAC-IS = - 59.9 + 1.3 \text{ Degree} + 14.3 \text{ Weight} + 1.19 \text{ Degree*Weight}$$

$$RGH-DIS = 10 + 4.4 \text{ Degree} + 19.8 \text{ Weight} + 1.06 \text{ Degree*Weight}$$

Where,

Degree = walkway gradient (in degrees),

Weight = load weight transferred by the cart (kg).

It should be noted that these equations were developed using three walkway gradients (0°, 5° and 10°) and three load conditions (20, 30, and 40 kg). A linear relationship was assumed between the joint loading, and walkway gradient and load weight.

CHAPTER 8: CONCLUSIONS

8.1 Conclusions

The main conclusions of this study are as follows:

(1) In addition to the load weight, effect of walkway gradient and direction of force application on the loading of low back and shoulder joints during cart pushing and pulling exertions were studied to fill the knowledge gaps in the existing literature. It was found that in addition to the load weight, walkway gradient and direction of force application had a significant effect on the loading of L5S1, sternoclavicular, acromioclavicular and glenohumeral joints. Uphill pushing exertions were found to be more strenuous than the downhill pulling exertions.

(2) The compression forces acting at the L5S1 joint at extreme task conditions (10° ramp, 40 kg load weight) were found to be lower than the recommended safe loading limit. However, loading of the L5S1 joint in the anterior-posterior (AP) direction was found to exceed the recommended safe loading limit during uphill pushing exertions performed along a 10° ramp at 30 and 40 kg weight conditions. This further suggests that, anterior-posterior shear loading at the L5S1 joint should be considered when assessing the risk of low back musculoskeletal disorders due to pushing and pulling activities.

(3) In this study, for the first time, quantitative loading of the three shoulder complex joints, sternoclavicular, acromioclavicular and glenohumeral joint, in three anatomical directions during cart pushing and pulling exertions were reported. Among the three joints, higher levels of loading were observed for the acromioclavicular and glenohumeral joints. In the existing literature, the focus has always been on the glenohumeral joint and loading of the acromioclavicular joints was not evaluated. The results of this research show that the loading of the acromioclavicular joint was comparable with the glenohumeral joint, further suggesting that the loading of the acromioclavicular joint should be considered, in addition to the glenohumeral joint, while evaluating risk of shoulder musculoskeletal disorders due to pushing and pulling activities.

- Acromioclavicular and glenohumeral joints were loaded to higher levels of forces (> 500 N) at a number of instances during pushing/pulling exertions evaluated in this study. Accurate estimate in terms of risk of injuries cannot be made because of the lack of information on the safe loading limits of these joints. However, based on the peak forces acting at these joints in the three anatomical directions, it can be concluded that during uphill pushing exertions, shoulder joint injury may occur due to the higher shear forces in the distraction (DIS) direction for the glenohumeral joint and higher compression (inferior-superior) forces for the acromioclavicular joint.

8.2 Future Work

The results of this study were obtained based on dynamic pushing/pulling activities performed on the wooden walkway using only one type of cart. Further studies should investigate the effect of different types of surfaces and carts on the musculoskeletal loading during pushing and pulling activities. Furthermore, there is a need to investigate a wider range of gradients since a strong interaction effect between gradient and direction of force application on the musculoskeletal loading was observed in this study. Future study with a wider range of gradients may assist in identifying a more accurate relationship between musculoskeletal loading and pushing/pulling exertions performed over inclined surfaces, further allowing development of a more accurate mathematical equation that could be used for the assessment of risk of low back and shoulder MSD.

Future study should also look at a larger, more diverse working population with manual materials handling experience to determine how well the trends observed in the current study could be applied to the working population.

One of the main contributions of this study is the quantitative assessment of the loading of three shoulder joints during dynamic cart pushing/pulling tasks. In fact this is the first study that reports this type of data. Based on the findings of this study it was identified that acromioclavicular and glenohumeral joints were loaded to higher levels of forces (> 500 N) at various instances. Because of the lack of data on the tolerance limits of these joints, accurate

assessment of the risk of shoulder joint injuries could not be presented. There is a strong need for the future studies that could provide safe loading limits for these joints.

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APPENDIX A: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Physical Activity Readiness Questionnaire (PAR-Q)

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

YES NO

☐	☐	1. Has your doctor ever said you have a heart trouble and should only do physical activity recommended by a doctor?
☐	☐	2. Do you frequently suffer from chest pain?
☐	☐	3. Do you often faint or have spells of severe dizziness?
☐	☐	4. Has your doctor ever said your blood pressure was too high?
☐	☐	5. Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by, or might be made worse with exercise.
☐	☐	6. Is there any good physical reason why you should not follow an activity program even if you want to?
☐	☐	7. Are you 65 and not accustomed to vigorous exercise?

If you answer “yes” to any question, vigorous exercise or exercise testing should be postponed. Medical clearance may be necessary.

I have read this questionnaire, I understand it does not provide medical assessment in lieu of a physical examination by a physician.

Participant’s signature: _____

Date: _____

Investigator’s signature: _____

Date: _____

Adapted from PAR-Q validation report, British Columbia department of Health, June 1975.

Reference: BQ Hafen, WWK Hoeger (1994), Wellness: Guidelines for a healthy lifestyle. Englewood, CO: Morton Pub. Co.

APPENDIX B: CONSENT AND INFORMATION FORM

CONSENT AND INFORMATION FORM

OMR ICF

Principal Investigator: Nimbarte, Ashish
Department: ENGINEERING - Ind./Mgt. Sys. Engineering
Tracking Number: H-22994

Study Title: Effects of Load and Gradient on Musculoskeletal Loading during Dynamic Two-wheeled Cart Pushing and Pulling

Co-Investigator(s):
Sun, Yun

Sponsor

Contact Persons

In the event you experience any side effects or injury related to this research, you should contact Dr. Nimbarte at 304/293-9473. (After hours contact Dr. Nimbarte at 225/226-8813.)
If you have any questions, concerns, or complaints about this research, you can contact Dr. Nimbarte at 304/293-9473 or Yun Sun at 304/293-9669.

If you have any questions, concerns, or complaints about this research that are not answered by the research team, you can contact the IRB Office at 304/293-7073. You can also call this number if you cannot talk to the research team or want to talk to someone else.

Introduction

You, _____, have been asked to participate in this research study, which has been explained to you by Dr. Ashish Nimbarte, Ph.D., and Yun Sun, M.S.. This study is being conducted by Dr. Ashish Nimbarte, Ph.D. and Yun Sun, M.S. in the Department of Industrial and

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Initials

Date

Management Systems Engineering (IMSE) at West Virginia University. This research is being conducted to fulfill the requirements for a doctoral dissertation of Ms. Yun Sun in the area of Occupational Safety and Health in the Department of IMSE at West Virginia University, under the supervision of Dr. Nimbarte.

Purposes of the Study

The purpose of this study is to learn more about biomechanical loading of major body joints and segments during dynamic cart pushing and pulling tasks under varying task demands. WVU expects to enroll approximately twenty male subjects.

Description of Procedures

Using a two-wheeled hand cart, the experiment will be conducted in three different loading states (20, 30 and 40 kg) on three different gradients (0°, 5° and 10°) of the wooden walkway during pushing and pulling. The study will take approximately 2 hours to complete from the time you arrived in the lab. Each trial consists of three successive pushing or pulling maneuvers over a distance of about 5 m of wooden walkway, which ensured a sufficient coefficient of friction to avoid slipping. Between these maneuvers, the participant will be allowed to rest for about 5 s. The entire measurement period for a trial amounts to a maximum of 45 s. Between the trials of varying gradients, there will be a recovery break lasting at least 10 min, during which the test set-up for a ramped pathway are modified. Tasks were designed to ensure that participants would not exceed accepted levels of energy expenditure. You may stop participating at any time, and for any reason.

Risks and Discomforts

It is possible that participants may experience some soreness in their right shoulder and arm shortly after completing the study due to the repeated pulling of the loaded cart on a ramped walkway. With the sufficient rest periods designed between each set of pulling tasks, the risk of injury as a result of participating in this study is minimal. Furthermore, at any time during the study, if you feel uncomfortable with any method or performing the requirements, you will be allowed to withdraw from the study without any penalty. In case of muscle or ligament strain (chances of which are very slim) you will be referred to Family Medicine Center at West Virginia University.

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Alternatives

You do not have to participate in this study.

Benefits

You may not receive any direct benefit from this study. The successful completion of this study will allow us to establish a new method to quantify the loading of the musculoskeletal system during a variety of cart push and pull exertions. It is expected that, this new knowledge will allow us to more precisely identify, the physical risk factors associated with work-related musculoskeletal disorders. The findings of this research are expected to have a positive impact on the health of the worker in various occupational groups because, by using the results of this study, workplace methods and/or designs could be appropriately modified to reduce the incidence of excessive musculoskeletal loading, further preventing the development of musculoskeletal disorders.

Financial Considerations

No monetary compensation will be given for participating in this study and participants do not incur any costs as a result of participation in the study.

Voluntary Compensation

It is very important for you to understand that neither the investigator nor WVU or its associated affiliates has the funds set aside to pay for the cost of lost work wages or any care or treatment that might be necessary because you get hurt or sick taking part in this study. Any injuries that may result from this study would not be eligible for Workers' Compensation as this is not job-related injury. Understand that any treatments necessary will be billed to the participant or to your personal health insurance, and you may wish to consult your insurance provider before participating in this study.

Confidentiality

Any information about you that is obtained as a result of your participation in this research will be kept as confidential as legally possible. Your research records and test results, just like hospital records, may be subpoenaed by court order or may be inspected by federal regulatory authorities without your additional consent. In any publications that result from this research, neither your name nor any information from which you might be identified will be published without your consent.

Voluntary Participation

Participation in this study is voluntary. You are free to withdraw your consent to participate in this study at any time. Refusal to participate or withdrawal will not affect your future care, [or your employee status at West Virginia University or your class standing or grades, as appropriate] and will involve no penalty to you. In the event new information becomes available that may affect your willingness to participate in this study, this information will be given to you so that you can make an informed decision about whether or not to continue your participation. You have been given the opportunity to ask questions about the research, and you have received answers concerning areas you did not understand.

Upon signing this form, you will receive a copy.

I willingly consent to participate in this research.

_____ Signature of Subject or Subjects Legal Representative	_____ Printed Name	_____ Date	_____ Time	_____
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The participant has had the opportunity to have questions addressed. The participant willingly agrees to be in the study.

_____ Signature of Subject or Subjects Legal Representative	_____ Printed Name	_____ Date	_____ Time	_____
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APPENDIX C: SAMPLE SIZE CALCULATIONS

Table C-1: Sample size calculations for Model 1

Dependent Variables	c	λ	ν_1	ν_2	β	Power (1- β)	c_1	λ	ν_1	ν_2	β	Power (1- β)	c_2	λ	ν_1	ν_2	β	Power (1- β)	c_3	λ	ν_1	ν_2	β	Power (1- β)
L5S1-ML	5	5.40	4	8	0.00	1.00																		
L5S1-PD	5	4.48	4	8	0.07	0.93																		
L5S1-AP	5	3.59	4	8	0.14	0.86	6	3.91	5	10	0.05	0.95												
RSC-ML	5	2.05	4	8	0.50	0.50	6	2.20	5	10	0.34	0.66	7	2.34	6	12	0.20	0.80	8	2.48	7	14	0.10	0.90
RSC-IS	5	2.56	4	8	0.38	0.62	6	2.77	5	10	0.16	0.84	7	2.96	6	12	0.08	0.92						
RSC-AP	5	2.51	4	8	0.40	0.60	6	2.72	5	10	0.21	0.79	7	2.90	6	12	0.08	0.92						
RAC-ML	5	4.19	4	8	0.08	0.92																		
RAC-IS	5	4.30	4	8	0.08	0.92																		
RAC-AP	5	4.69	4	8	0.06	0.95																		
RGH-DIS	5	4.65	4	8	0.06	0.95																		
RGH-IS	5	4.56	4	8	0.06	0.94																		
RGH-AP	5	6.99	4	8	0.00	1.00																		

Table C-2: Sample size calculations for Model 2

Dependent Variables	c	λ	ν_1	ν_2	β	Power (1- β)	c_1	λ	ν_1	ν_2	β	Power (1- β)	c_2	λ	ν_1	ν_2	β	Power (1- β)	c_3	λ	ν_1	ν_2	β	Power (1- β)
L5S1-ML	5	3.79	4	44	0.06	0.95																		
L5S1-PD	5	2.69	4	44	0.19	0.81	6	2.91	5	55	0.08	0.92												
L5S1-AP	5	3.33	4	44	0.08	0.93																		
RSC-ML	5	6.67	4	44	0.00	1.00																		
RSC-IS	5	3.51	4	44	0.07	0.93																		
RSC-AP	5	2.17	4	44	0.37	0.63	6	2.33	5	55	0.17	0.83	7	2.49	6	66	0.07	0.93						
RAC-ML	5	1.76	4	44	0.57	0.43	6	1.87	5	55	0.40	0.60	7	1.98	6	66	0.19	0.81	8	2.08	7	77	0.10	0.90
RAC-IS	5	3.08	4	44	0.13	0.87	6	3.34	5	55	0.05	0.95												
RAC-AP	5	2.25	4	44	0.30	0.70	6	2.43	5	55	0.22	0.78	7	2.59	6	66	0.05	0.95						
RGH-DIS	5	3.08	4	44	0.13	0.87	6	3.34	5	55	0.05	0.95												
RGH-IS	5	5.62	4	44	0.00	1.00																		
RGH-AP	5	3.82	4	44	0.05	0.95																		

APPENDIX D: ANOVA TABLES FOR MODEL VALIDATION

ANOVA of Session 1: RMSE, r versus Subject, Weight

Analysis of Variance for RMSE, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	5	44.862	44.862	8.972	3.12	0.059
Weight	2	19.683	19.683	9.841	3.42	0.074
Error	10	28.759	28.759	2.876		
Total	17	93.303				

S = 1.69585 R-Sq = 69.18% R-Sq(adj) = 47.60%

Analysis of Variance for r, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	5	0.0089829	0.0089829	0.0017966	3.38	0.048
Weight	2	0.0006601	0.0006601	0.0003301	0.62	0.557
Error	10	0.0053232	0.0053232	0.0005323		
Total	17	0.0149663				

S = 0.0230721 R-Sq = 64.43% R-Sq(adj) = 39.53%

ANOVA of Session 2: RMSE, r versus Subject, Degree, Weight, Direction

Analysis of Variance for RMSE, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	5	1163.395	1163.395	232.679	49.40	0.000
Degree	1	5.752	5.752	5.752	1.22	0.274
Weight	2	55.581	55.581	27.790	5.90	0.005
Direction	1	35.182	35.182	35.182	7.47	0.008
Degree*Weight	2	5.317	5.317	2.658	0.56	0.572
Degree*Direction	1	28.969	28.969	28.969	6.15	0.016
Weight*Direction	2	1.768	1.768	0.884	0.19	0.829
Degree*Weight*Direction	2	4.223	4.223	2.111	0.45	0.641
Error	55	259.045	259.045	4.710		
Total	71	1559.230				

S = 2.17023 R-Sq = 83.39% R-Sq(adj) = 78.55%

Analysis of Variance for r, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	5	0.038139	0.038139	0.007628	5.92	0.000
Degree	1	0.017703	0.017703	0.017703	13.74	0.000
Weight	2	0.001320	0.001320	0.000660	0.51	0.602
Direction	1	0.001522	0.001522	0.001522	1.18	0.282
Degree*Weight	2	0.001770	0.001770	0.000885	0.69	0.508
Degree*Direction	1	0.000416	0.000416	0.000416	0.32	0.572
Weight*Direction	2	0.001361	0.001361	0.000680	0.53	0.593
Degree*Weight*Direction	2	0.000858	0.000858	0.000429	0.33	0.718
Error	55	0.070885	0.070885	0.001289		
Total	71	0.133973				

S = 0.0359001 R-Sq = 47.09% R-Sq(adj) = 31.70%

Figure D-1: ANOVA Tables for model validation

APPENDIX E: PARTICIPANTS' ANTHROPOMETRIC DATA

Table E-1: Participants' anthropometric data

Subject No.	1	2	3	4	5	6	7	8	9	10	11	12	All
Age (years)	26	28	24	24	23	22	21	22	23	24	25	23	23.75 (1.91)
Body mass (kg)	65.5	77	63.6	75	59.3	70.5	72	73	73.5	68.5	66.5	66.3	69.23 (5.19)
Height (cm)	169	165	173	169.5	176	171	177	180	171	167	176	170	172.04 (4.44)
Head height (cm)	18.5	15.4	16.3	18.4	18.1	16.5	18.4	16.8	18	18	17.3	17.2	17.41 (0.99)
Trunk height (cm)	45.4	47.1	54.8	49.3	53	46	53.5	52.5	48.4	44.5	55	49.6	49.93 (3.75)
Upper arm length (cm)	32.5	32.5	37	34	32.5	35	35.2	36.6	35.5	34.5	35.5	31.8	34.38 (1.73)
Lower arm length (cm)	27.2	24.3	27.1	28.4	30	28.5	27	30.1	26.7	25.8	29.1	23.9	27.34 (2.01)
Hand length (cm)	18.5	17.5	18.4	17.3	18.1	18.8	17.7	20.5	18.3	17.8	18.4	17.7	18.25 (0.84)
Hand breadth (cm)	8.5	8	8.55	8.6	9.1	9.5	7.8	8.7	7.5	8.2	8.6	7.7	8.40 (0.58)
Pelvis width (cm)	31.2	32.5	30.43	32.7	34.5	32.3	32.4	34	31.3	28.9	28.6	27.4	31.35 (2.18)
Thigh length (cm)	43	39	38.16	41.7	45.3	44.7	42.5	40.4	40.7	43.8	48.4	43.9	42.63 (2.87)
Shank length (cm)	43.1	37.5	41.03	41.5	44	43.5	42	43.4	42.4	38.1	41	37.8	41.28 (2.31)
Foot length (cm)	26.7	27.5	26.1	26.6	28	26.1	25	30.5	26.6	26	26.7	26	26.82 (1.39)

APPENDIX F: RAW GRF DATA OF RIGHT AND LEFT FOOT

Table F-1: Raw GRF data for right and left foot in Session 1

Subject no.	Weight	Right Foot						Left Foot					
		Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
1	20	65	53	655	79	22	5	70	82	640	36	27	8
1	30	62	60	654	54	33	2	56	93	650	57	24	8
1	40	65	77	650	41	38	3	64	107	673	74	6	10
2	20	56	63	745	81	59	10	58	48	729	31	52	7
2	30	58	78	735	72	46	10	54	58	720	45	48	6
2	40	63	88	724	116	35	9	51	73	714	104	52	10
3	20	50	58	616	65	31	5	58	36	580	45	27	5
3	30	51	65	610	65	30	5	50	40	605	35	35	4
3	40	41	68	605	80	42	2	39	42	607	40	40	6
4	20	59	56	745	99	48	9	60	40	716	33	35	4
4	30	48	69	739	69	41	7	59	44	712	30	41	4
4	40	63	87	729	84	47	9	57	50	724	50	43	5
5	20	51	66	611	68	27	6	54	38	588	33	30	5
5	30	52	69	606	81	26	4	58	44	587	59	31	6
5	40	41	78	600	80	44	2	41	52	585	35	40	7
6	20	39	24	679	41	59	3	43	39	677	41	43	3
6	30	49	50	670	99	52	8	46	40	673	48	46	5
6	40	46	68	667	60	56	4	40	56	671	94	43	3
7	20	76	69	721	101	41	13	73	55	728	36	32	2
7	30	65	71	711	83	40	10	67	65	696	62	41	2
7	40	67	87	707	71	25	10	69	66	680	51	36	3
8	20	60	85	731	117	48	7	70	65	727	39	28	7
8	30	58	100	724	60	38	3	73	72	717	95	15	7
8	40	60	119	717	86	44	4	73	97	710	27	25	5
9	20	55	60	737	78	56	7	55	45	757	28	49	4
9	30	56	65	722	69	43	7	51	55	726	42	45	3
9	40	61	77	712	113	32	6	48	80	708	101	49	7
10	20	55	77	687	36	47	4	49	70	674	55	34	6
10	30	39	78	680	39	42	5	55	110	669	48	31	7
10	40	62	106	668	40	50	5	56	133	653	82	24	6

Subject no.	Weight	Right Foot						Left Foot					
		Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
11	20	41	25	650	42	57	4	44	40	656	42	44	6
11	30	51	50	662	97	56	5	47	55	670	49	45	5
11	40	46	64	667	61	57	6	45	56	678	87	45	7
12	20	75	65	665	84	27	10	75	87	651	41	24	6
12	30	71	77	662	59	38	7	61	98	645	62	21	4
12	40	67	88	655	46	43	5	69	110	668	79	3	4

Table F-2: Raw GRF data for right and left foot in Session 2

Subject no.	Degree	Weight	Direction	Right Foot						Left Foot					
				Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
1	5	20	1	43	151	694	88	37	2	37	99	630	23	48	9
1	5	30	1	46	143	669	76	37	1	50	130	663	42	43	11
1	5	40	1	55	176	645	30	37	6	44	141	605	48	28	10
1	5	20	2	65	140	729	51	38	11	45	145	695	51	29	1
1	5	30	2	66	144	721	54	52	12	52	154	706	56	34	0
1	5	40	2	71	139	695	51	55	13	37	118	712	53	22	6
1	10	20	1	31	189	643	68	48	14	44	198	619	65	16	10
1	10	30	1	37	204	597	34	50	17	52	204	591	73	11	9
1	10	40	1	29	231	591	25	39	20	60	188	590	75	12	11
1	10	20	2	56	166	711	29	56	13	56	165	657	28	10	5
1	10	30	2	49	144	676	67	50	11	45	174	660	35	48	12
1	10	40	2	53	128	659	49	50	14	45	169	668	30	40	11
2	5	20	1	60	92	638	26	34	8	87	92	714	39	30	5
2	5	30	1	64	137	625	40	48	18	63	99	637	63	43	13
2	5	40	1	54	174	588	62	44	10	51	116	647	31	40	10
2	5	20	2	70	126	728	68	42	9	97	178	737	51	43	9
2	5	30	2	74	119	722	70	41	9	88	196	703	71	45	11
2	5	40	2	82	129	683	75	39	8	93	209	692	43	40	11
2	10	20	1	55	184	628	36	47	23	69	159	669	81	59	28
2	10	30	1	50	196	618	17	61	24	80	184	689	56	21	14
2	10	40	1	59	220	746	50	45	19	53	215	713	48	44	20

Subject no.	Degree	Weight	Direction	Right Foot						Left Foot					
				Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
2	10	20	2	60	150	693	75	35	11	100	229	672	70	53	19
2	10	30	2	56	147	703	71	50	9	90	234	680	72	50	15
2	10	40	2	124	228	680	52	39	15	99	256	692	34	42	12
3	5	20	1	64	143	640	28	36	10	89	101	716	41	32	7
3	5	30	1	63	169	630	35	43	13	58	87	632	58	38	8
3	5	40	1	49	178	561	55	37	3	44	109	640	24	33	3
3	5	20	2	86	128	713	38	29	4	61	133	637	25	33	7
3	5	30	2	71	134	682	56	45	11	41	149	634	20	37	7
3	5	40	2	63	125	630	59	42	11	54	130	624	235	33	10
3	10	20	1	45	183	617	25	36	12	58	172	658	70	48	17
3	10	30	1	47	192	614	13	57	20	76	155	685	52	17	10
3	10	40	1	28	202	551	30	38	14	51	191	549	24	11	3
3	10	20	2	58	170	650	70	48	17	44	180	610	20	36	12
3	10	30	2	56	178	649	67	39	12	40	190	620	18	37	14
3	10	40	2	51	180	646	57	27	10	28	206	623	19	53	17
4	5	20	1	44	114	705	45	53	5	64	111	741	67	44	10
4	5	30	1	39	126	717	65	66	9	58	116	661	45	36	4
4	5	40	1	58	142	773	56	58	6	57	132	740	30	40	7
4	5	20	2	71	157	779	86	50	14	73	178	814	32	41	9
4	5	30	2	67	120	791	47	59	9	59	114	745	39	37	5
4	5	40	2	71	148	809	79	33	12	65	159	801	32	47	9
4	10	20	1	53	209	690	25	51	15	58	207	752	29	37	10
4	10	30	1	61	220	736	19	52	19	67	195	765	65	30	17
4	10	40	1	78	230	772	48	44	10	78	212	764	63	18	12
4	10	20	2	79	205	775	71	50	19	66	230	754	38	28	11
4	10	30	2	96	223	805	87	53	19	65	229	787	46	35	13
4	10	40	2	73	257	818	80	59	18	79	205	800	20	34	8
5	5	20	1	44	140	560	28	28	6	50	91	578	11	27	2
5	5	30	1	70	138	620	75	22	6	70	129	620	21	29	4
5	5	40	1	34	205	643	62	52	15	77	175	708	74	49	19
5	5	20	2	89	131	716	41	32	7	64	136	640	28	36	10
5	5	30	2	73	136	684	58	47	13	43	151	636	22	39	9
5	5	40	2	64	155	636	59	42	11	55	135	629	30	34	10

Subject no.	Degree	Weight	Direction	Right Foot						Left Foot					
				Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
5	10	20	1	63	189	562	64	43	12	39	193	528	25	19	6
5	10	30	1	44	200	581	71	43	16	46	197	591	25	29	8
5	10	40	1	19	201	551	23	38	14	51	191	549	35	11	4
5	10	20	2	58	172	659	70	48	17	45	184	610	25	37	12
5	10	30	2	76	155	685	52	17	10	47	192	614	12	57	20
5	10	40	2	52	178	645	57	27	10	30	207	623	25	54	19
6	5	20	1	51	146	679	97	49	3	51	127	682	30	47	7
6	5	30	1	49	136	700	85	32	5	57	126	644	57	47	7
6	5	40	1	46	158	638	77	46	10	48	127	656	57	46	12
6	5	20	2	51	151	697	56	44	8	56	181	678	73	50	14
6	5	30	2	58	125	744	92	52	10	50	115	708	47	56	8
6	5	40	2	56	169	731	91	36	11	60	175	759	91	52	11
6	10	20	1	40	214	670	64	45	13	70	173	663	33	37	9
6	10	30	1	32	217	678	60	38	15	56	190	605	22	47	14
6	10	40	1	48	234	660	75	56	25	66	173	641	61	20	7
6	10	20	2	51	151	697	56	44	8	56	181	678	72	50	14
6	10	30	2	54	149	682	72	47	7	50	179	661	40	53	17
6	10	40	2	58	133	664	54	47	11	50	174	673	32	45	16
7	5	20	1	64	169	725	98	28	5	62	125	643	35	36	6
7	5	30	1	61	174	731	85	38	3	59	141	687	22	41	5
7	5	40	1	62	180	699	85	34	4	52	147	664	24	34	5
7	5	20	2	67	123	793	65	39	6	98	186	821	48	40	6
7	5	30	2	71	116	748	67	38	6	86	175	800	68	42	8
7	5	40	2	79	136	792	72	36	5	91	186	773	40	37	8
7	10	20	1	50	192	655	88	39	6	71	160	648	37	31	7
7	10	30	1	54	219	674	77	36	4	68	166	632	44	37	11
7	10	40	1	53	231	657	57	32	11	67	184	677	85	30	7
7	10	20	2	57	147	841	72	32	8	104	226	801	67	50	16
7	10	30	2	53	144	814	68	47	6	93	211	837	69	47	12
7	10	40	2	65	122	753	50	26	10	78	193	856	105	27	7
8	5	20	1	51	157	664	41	22	5	63	116	668	74	34	9
8	5	30	1	57	172	641	62	34	6	77	133	647	32	7	6
8	5	40	1	75	185	711	21	31	4	77	153	736	25	15	5

Subject no.	Degree	Weight	Direction	Right Foot						Left Foot					
				Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
8	5	20	2	63	110	719	36	38	6	84	145	726	22	22	7
8	5	30	2	83	119	717	76	40	12	94	193	771	38	4	8
8	5	40	2	69	109	743	56	31	7	76	176	776	25	30	10
8	10	20	1	58	172	636	42	34	19	68	170	702	67	24	7
8	10	30	1	41	217	658	50	35	19	68	196	645	18	22	5
8	10	40	1	65	193	753	13	44	21	56	214	703	51	25	6
8	10	20	2	72	140	733	78	37	5	73	166	753	55	38	25
8	10	30	2	56	128	682	63	35	5	54	168	703	36	28	17
8	10	40	2	67	184	763	73	42	7	42	162	662	45	31	15
9	5	20	1	39	109	700	40	48	1	59	106	736	62	39	5
9	5	30	1	41	128	719	67	68	11	60	118	663	47	38	6
9	5	40	1	62	146	777	60	62	10	61	136	744	34	44	11
9	5	20	2	67	156	725	65	39	6	98	175	734	48	40	6
9	5	30	2	71	143	719	67	38	6	86	193	700	68	42	8
9	5	40	2	79	146	680	72	36	5	91	206	689	40	37	8
9	10	20	1	61	217	698	33	59	23	66	215	760	37	45	18
9	10	30	1	62	221	737	20	53	20	68	196	766	66	31	18
9	10	40	1	61	257	743	47	42	16	50	212	710	45	41	17
9	10	20	2	57	147	690	72	32	8	104	236	689	67	50	16
9	10	30	2	53	144	700	68	47	6	93	231	677	69	47	12
9	10	40	2	121	225	677	49	36	12	98	253	669	31	39	9
10	5	20	1	51	132	631	105	51	3	62	134	668	45	12	4
10	5	30	1	89	168	663	62	46	9	51	174	670	70	41	13
10	5	40	1	71	180	670	110	104	24	64	228	738	76	46	12
10	5	20	2	117	148	850	39	50	4	85	223	742	39	59	15
10	5	30	2	69	209	825	84	46	16	101	240	770	37	51	22
10	5	40	2	78	217	884	90	81	24	111	287	790	80	32	12
10	10	20	1	51	200	682	71	52	17	91	188	766	87	32	13
10	10	30	1	70	204	633	76	45	10	62	223	724	74	17	14
10	10	40	1	67	283	704	79	67	23	82	314	700	104	33	14
10	10	20	2	80	306	647	70	76	16	88	275	675	22	76	34
10	10	30	2	105	244	645	52	110	17	107	289	678	41	81	31
10	10	40	2	93	268	678	78	66	8	98	300	661	77	89	45

Subject no.	Degree	Weight	Direction	Right Foot						Left Foot					
				Fx	Fy	Fz	Mx	My	Mz	Fx	Fy	Fz	Mx	My	Mz
11	5	20	1	48	116	679	96	58	5	56	128	682	45	48	8
11	5	30	1	50	136	689	88	54	6	56	127	644	56	49	9
11	5	40	1	47	158	668	76	45	7	49	130	656	55	47	11
11	5	20	2	52	152	697	54	45	9	60	181	678	74	51	13
11	5	30	2	57	89	744	90	51	11	49	115	708	99	54	9
11	5	40	2	59	167	731	87	38	12	59	175	759	89	50	12
11	10	20	1	45	214	670	63	55	12	72	171	663	34	39	10
11	10	30	1	33	217	678	59	48	14	55	187	605	25	46	13
11	10	40	1	50	234	660	73	55	23	64	175	641	60	23	8
11	10	20	2	52	154	697	59	45	9	55	161	670	69	49	13
11	10	30	2	55	156	682	70	49	8	49	179	661	42	53	16
11	10	40	2	59	137	664	53	46	11	49	174	673	30	46	17
12	5	20	1	48	156	699	93	42	4	42	104	635	28	45	6
12	5	30	1	51	148	674	81	42	6	55	135	668	47	40	8
12	5	40	1	60	181	625	35	42	11	49	146	610	53	25	7
12	5	20	2	70	155	734	56	35	8	50	160	690	56	34	6
12	5	30	2	71	149	726	59	49	9	57	159	701	61	39	5
12	5	40	2	76	122	700	56	52	10	42	123	737	58	27	11
12	10	20	1	36	194	648	73	53	19	49	203	624	70	13	7
12	10	30	1	42	209	602	39	55	22	57	209	596	78	8	6
12	10	40	1	34	236	596	30	44	25	65	193	595	80	9	8
12	10	20	2	61	181	716	34	53	10	61	160	672	33	15	10
12	10	30	2	54	149	681	72	47	8	50	179	673	40	53	17
12	10	40	2	58	133	664	54	47	11	50	174	673	35	45	16

APPENDIX G: RAW DATA OF MAJOR JOINT ANGLES

Table G-1: Raw major joint angle data in Session 1

Subject no.	Weight	Trunk	Right - Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
		Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
1	20	2.5	14.2	30.7	-35	48.1	15
1	30	17.1	32.2	37.1	40.6	58.3	12.1
1	40	9.5	-23.2	35.7	40.4	52.1	14.3
2	20	2.9	19.7	58.3	23.1	62.2	-13.2
2	30	4.5	18.1	61.1	27.4	64.1	12
2	40	6.6	19.4	55.2	27	63.9	11.9
3	20	-4.2	9	43.9	29.3	44.9	9.2
3	30	-7.3	8	44.7	29.5	47.6	16.1
3	40	-5.5	13.6	44	31.5	56.8	16.3
4	20	2.9	19.6	62	23.7	62.5	9.8
4	30	5.1	18.1	60.9	32.6	65.4	11.7
4	40	7	24.6	58.1	29.9	65.3	-14.7
5	20	14.7	32.8	95	14.3	52	13
5	30	16.7	26	116.9	11.1	53	15.1
5	40	13.2	11.1	54.1	10.9	50	11.6
6	20	13.4	26.1	96.2	12.7	49.6	13.3
6	30	16.4	30.7	102.2	14.4	55.4	14.8
6	40	19.7	35.6	108.6	16.3	61	16.9
7	20	-7.6	-18	91.4	21.3	45.1	19.2
7	30	5.4	-17.6	85	18.5	47.8	18.8
7	40	-10.4	-16	68.3	21	41.7	16.6
8	20	-8.3	-18.5	80.3	29.2	39.2	-15.9
8	30	-7.1	-16.2	77	32.4	47.1	-17.2
8	40	-8.1	-8.8	73.8	33.4	49.3	-18.6
9	20	17.7	19.6	53.6	15	59.8	-15.7
9	30	18.1	14.7	58.2	16	62.7	14.6
9	40	16.9	17	54.1	18	64	14.7
10	20	5.5	-6.2	99.1	22.9	46.1	18.1
10	30	-5	-20.5	87.4	20	50.4	15.7
10	40	4.2	-21.5	114.4	20.8	49.7	17.1

Subject no.	Weight	Trunk	Right - Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
		Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
11	20	8.1	24.7	58.2	17.5	60.7	20
11	30	8	21.9	60.6	18.1	60.4	20.4
11	40	8	19	69.7	18.6	60.2	20.6
12	20	4	32.9	39.1	21.4	63.2	18.7
12	30	5.7	28.2	43.7	21.6	61.9	19.6
12	40	6.6	20.2	53.3	21.3	60.1	20.3

Table G-2: Raw major joint angle data in Session 2

Subject no.	Degree	Weight	Direction	Trunk	Right -Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
				Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
1	5	20	1	6	21	39	47.7	49.9	19.7
1	5	30	1	12.4	45.5	39	51.7	51.9	23.1
1	5	40	1	6.4	29.4	47.1	53.6	56.5	24.3
1	5	20	2	12.5	17.3	45.4	29.7	64.4	-19.9
1	5	30	2	21	-172.3	47.7	36.6	66.2	23
1	5	40	2	11	15.6	42.1	32.9	55.7	-24.2
1	10	20	1	6.3	36	55.4	59.6	57.3	30.3
1	10	30	1	12.8	57.9	42.7	68.8	63.2	-48.5
1	10	40	1	14.3	55.9	57.7	72.2	62.4	37.9
1	10	20	2	15.6	25.2	45.7	34.2	70	-34.9
1	10	30	2	23	36.2	49	35.9	71.5	-38
1	10	40	2	23.32	30.9	43.1	40.3	75.4	-43.1
2	5	20	1	13	35	68.2	34.6	65.8	17
2	5	30	1	13.9	40.2	52.6	30	68.8	24.7
2	5	40	1	12.4	40.9	64.4	31.2	63.5	21.5
2	5	20	2	14.9	22.6	55.5	17	71.1	16.2
2	5	30	2	13.8	21.5	48.3	18.7	69.6	15.9
2	5	40	2	13.1	20.7	59.1	20.3	70.4	16.6
2	10	20	1	10.5	30.3	81.1	52	61.5	28.6
2	10	30	1	10.5	31.1	79.2	46.3	61	30.2

Subject no.	Degree	Weight	Direction	Trunk	Right -Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
				Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
2	10	40	1	9.8	19.2	89.4	45.9	62.5	28.7
2	10	20	2	13.9	24.4	39.8	17.8	71.8	14.9
2	10	30	2	17.8	22.9	40.5	23.6	76.9	18.1
2	10	40	2	17.7	26.7	51	24.1	73.5	14
3	5	20	1	-4.5	41.2	41.5	49.4	51.4	21.8
3	5	30	1	-6.8	24.5	70.8	41.1	50.9	23.1
3	5	40	1	-5.8	38.9	51.5	44.2	41.3	26.8
3	5	20	2	-4.3	15.5	44.1	18.7	47.6	15.8
3	5	30	2	3.8	15.8	39.1	25.7	52.2	17.8
3	5	40	2	5.3	22	37.1	30	70.8	18.5
3	10	20	1	6.7	53	55	51.5	45.1	35.3
3	10	30	1	-8.3	46.5	50.5	48.8	50.1	35.4
3	10	40	1	-5.2	23.9	88	66.8	56.9	38.3
3	10	20	2	6.4	20.1	38.2	27.8	79.9	18.5
3	10	30	2	9.6	31.4	35.9	31.9	87.4	20.7
3	10	40	2	4.5	15.5	41	32.3	78.5	20.8
4	5	20	1	13	35	71.3	41.1	67.7	18.4
4	5	30	1	16	40.2	55.5	37.5	69.5	24.6
4	5	40	1	12.3	41.2	64.3	40.5	66.8	21.7
4	5	20	2	14.9	23.9	95.4	21.4	73.6	16.4
4	5	30	2	13.8	20.5	50	20.6	71.4	16.1
4	5	40	2	14.7	21.7	56.9	20.7	70.5	16.6
4	10	20	1	16.4	41	80.8	52.7	78.5	28.5
4	10	30	1	13.6	37	97.8	54.7	73.7	30.2
4	10	40	1	10.9	26	89.6	54.3	66.9	29.4
4	10	20	2	13.9	24.6	44.7	18.3	74.1	15.3
4	10	30	2	21.3	27.7	40.5	24	77.4	18.2
4	10	40	2	20.9	26.7	53.1	24.6	73.9	14.1
5	5	20	1	11.1	41.2	108.4	27.4	51.5	20.6
5	5	30	1	15	58.1	70.9	33.5	52.3	22.1
5	5	40	1	15.7	66.7	66	40.2	58.5	27.1
5	5	20	2	8.5	10.7	67.6	11.2	63.8	18.5

Subject no.	Degree	Weight	Direction	Trunk	Right -Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
				Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
5	5	30	2	9.7	15.5	73.9	9	68.2	22.1
5	5	40	2	11.2	18.9	69.3	-21.3	59.2	25
5	10	20	1	20	60.7	64	42.1	53.1	30.3
5	10	30	1	22.6	48	96.5	47.2	55.2	34.2
5	10	40	1	25.5	34.9	128.2	52.8	57.9	38.5
5	10	20	2	16.4	21.3	89.1	16.6	79.6	25.4
5	10	30	2	20.3	30.3	62.5	18	67.4	27.3
5	10	40	2	14.8	28	60.1	15.2	70.7	24.5
6	5	20	1	12.2	45.3	119.2	30.1	56.7	22.7
6	5	30	1	16.3	59.4	72.2	34.8	53.6	23.4
6	5	40	1	18.1	69.1	68.4	42.6	60.9	29.5
6	5	20	2	9.7	11.9	68.8	12.4	65	19.7
6	5	30	2	8.7	14.5	72.9	8	67.2	21.1
6	5	40	2	6.6	14.3	64.5	-29.7	66.5	22.7
6	10	20	1	22.2	62.9	66.2	44.3	55.3	32.5
6	10	30	1	23.5	48.9	97.4	48.1	56.1	35.1
6	10	40	1	28.4	37.8	131.1	55.7	60.8	41.4
6	10	20	2	16	20.9	88.7	16.2	79.2	25
6	10	30	2	19.1	29.1	61.3	16.8	66.2	26.1
6	10	40	2	15.6	28.8	60.9	16	71.5	25.3
7	5	20	1	9	-7.2	50	31	58.9	22
7	5	30	1	21.6	37.3	72.2	41.1	55.2	24.1
7	5	40	1	15	13.3	60.4	41.5	60.2	28.5
7	5	20	2	-7	11	46	15	19	19
7	5	30	2	17.3	4.5	52.2	13.3	55.5	18.3
7	5	40	2	15.5	6.5	48.5	13.2	63.5	21.8
7	10	20	1	29.8	47	77.4	38.1	55.6	32
7	10	30	1	29.7	45.8	78.1	54.7	55.8	36.7
7	10	40	1	12.7	21.6	87.5	50.2	62.3	40
7	10	20	2	27	9.9	60.6	15.5	58.8	19.1
7	10	30	2	16.9	8.1	56.4	16.6	69	24
7	10	40	2	13	4.5	48.7	16.7	61.5	15.5

Subject no.	Degree	Weight	Direction	Trunk	Right -Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
				Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
8	5	20	1	-2.9	8.9	69.3	43.7	53.8	-24.5
8	5	30	1	13.8	33.4	65.8	50.2	55.8	-21.1
8	5	40	1	6.7	-5.5	82.3	53.9	60	-25.1
8	5	20	2	-6.7	29.8	83.5	24.8	57	-26.9
8	5	30	2	3.3	9.1	59.2	38.3	69.1	-27.4
8	5	40	2	7.4	-9.5	68.4	35.1	73.6	-25.1
8	10	20	1	7.3	16.5	85.9	64.8	63.1	-27.9
8	10	30	1	7.6	-21.2	100	63.8	60	-32.3
8	10	40	1	9.6	-11.9	111.9	62	66.2	-47.3
8	10	20	2	3.9	-5.4	74.2	34	69.7	-35.1
8	10	30	2	8.9	22.5	70.8	38.8	75.3	-33.2
8	10	40	2	11.7	13.5	84.2	41.3	78.4	-38.4
9	5	20	1	30	28.8	54.3	24.2	60.6	-22.2
9	5	30	1	25.1	22	69.7	29	59.7	21.1
9	5	40	1	40.4	32.7	60.6	40.3	59.7	25.1
9	5	20	2	27.4	29.9	48.9	11.1	66.8	17.1
9	5	30	2	38.8	34.3	46.7	18.9	79.3	23.1
9	5	40	2	55.5	51.6	38.9	29	75.2	18.2
9	10	20	1	28.6	21	77	35.4	64	30.7
9	10	30	1	24.2	16.3	80.9	38.5	67.3	33.5
9	10	40	1	25.4	29.5	84.3	52.5	72.2	32.4
9	10	20	2	36.7	33.6	44.9	13	72.7	16.7
9	10	30	2	32.8	35.6	48.3	21.8	78.1	17
9	10	40	2	36.9	36.2	49.9	23.9	77.4	16.2
10	5	20	1	9	-7	49.8	30.9	58.9	22.4
10	5	30	1	20.4	36.1	71	39.9	54	22.9
10	5	40	1	13.8	12.1	59.2	40.3	59	27.3
10	5	20	2	-5.6	12.3	47.5	16.3	19.7	20.5
10	5	30	2	17.7	4.9	52.6	13.7	55.9	18.7
10	5	40	2	15.6	6.6	48.6	13.3	63.6	21.9
10	10	20	1	28.9	46.1	76.5	37.2	54.7	31.1
10	10	30	1	28.8	44.9	77.2	53.8	54.9	35.8

Subject no.	Degree	Weight	Direction	Trunk	Right -Shoulder	Right - Elbow	Right - Hip	Right - Knee	Right - Ankle
				Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension	Flexion/extension
10	10	40	1	11.8	21.4	81.3	60.4	55.1	43
10	10	20	2	26.1	9	59.7	14.6	57.9	18.2
10	10	30	2	17.4	8.4	56.9	17	69.3	24.5
10	10	40	2	12.1	3.4	47.6	15.6	60.4	14.4
11	5	20	1	8.4	33.8	74.4	25.7	60	24.7
11	5	30	1	9.4	37.3	73.2	27.1	59.8	26
11	5	40	1	10.5	41.8	72.3	29.2	60	28.8
11	5	20	2	12.8	24.9	60.9	14.4	65.3	24.1
11	5	30	2	13.88	23.4	62.76	-4.02	65.18	26.08
11	5	40	2	14.6	22.4	64	-16.3	65.1	27.4
11	10	20	1	9.6	27.5	76.1	36.6	62.8	33.6
11	10	30	1	8.4	24.7	80.74	42.84	63.88	36.84
11	10	40	1	6.6	20.5	87.7	52.2	65.5	41.7
11	10	20	2	14.7	21.8	56.7	-14.8	69.8	26.5
11	10	30	2	13.23	20.05	57.4	6.62	70.64	23.84
11	10	40	2	12.6	19.3	57.7	15.8	71	22.7
12	5	20	1	6.8	37.4	47.1	33.9	57.8	21.8
12	5	30	1	16.16	65.48	43.268	42.22	55	26.84
12	5	40	1	18.5	72.5	42.31	44.3	54.3	28.1
12	5	20	2	8.3	25	55.9	19.6	67.2	19.9
12	5	30	2	9.76	22.93	47.33	20.38	68.82	18.28
12	5	40	2	10.9	21.3	40.6	21	70.1	17
12	10	20	1	13.8	58	65.6	48.8	60.7	26
12	10	30	1	21.41	75.88	51.50	57.64	62.52	28.02
12	10	40	1	25.5	85.5	43.9	62.4	63.5	29.1
12	10	20	2	14.2	23	41.3	23.9	75.2	19.4
12	10	30	2	17.51	27.16	41.38	28.98	79.36	19.48
12	10	40	2	18.5	28.4	41.4	30.5	80.6	19.5

APPENDIX H: RAW DATA OF LOW BACK AND SHOULDER JOINT LOADING

Table H-1: Raw data of low back and shoulder joint loading in Session 1

Subject no.	Weight	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
1	20	107	889	339	53	86.3	41.8	245	283	302	522	284	244
1	30	155	1300	410	61.3	99.3	51	348	442	347	748	530	485
1	40	174	1730	516	68	118	51.9	516	874	400	820	624	558
2	20	32.4	797	156	32	68.4	22.3	195	217	188	346	148	125
2	30	46.4	998	192	38.6	87.5	25.1	274	298	225	550	136	168
2	40	48.8	1200	232	44	104	30.9	317	368	276	683	178	208
3	20	32.9	811	156	79.8	69	22.6	199	193	194	363	152	138
3	30	45.6	1000	193	38.5	87.4	25.5	280	305	230	553	137	167
3	40	117	1610	440	79	133	45	390	601	319	852	574	272
4	20	11.6	909	105	92	67	24.4	169	421	134	386	307	107
4	30	56.4	1180	188	135	110	29.9	356	501	237	730	466	252
4	40	40.1	1300	425	148	134	45	420	761	355	985	583	350
5	20	44.4	909	169	44.1	108	38.2	255	256	169	578	132	177
5	30	87.5	1245	379	102	197	48.9	448	566	303	713	384	323
5	40	76.1	1468	406	145	224	50.5	556	728	408	1260	645	367
6	20	37.7	653	126	22.8	78	23.6	188	229	90.4	398	111	142
6	30	44.5	727	119	37.1	92.4	27.9	220	257	107	477	167	169
6	40	55.5	1000	179	58	102	33.3	294	503	149	634	340	223
7	20	34.8	821	143	42.1	55.3	28.9	170	243	137	352	142	128
7	30	52.4	1040	200	52.3	93.5	31.8	300	317	214	713	232	221
7	40	63.9	1230	237	65	110	40.8	366	386	260	873	285	270
8	20	28.6	980	156	71.8	80.5	30.9	267	362	204	573	370	197
8	30	50.2	1040	160	113	136	36	311	498	204	614	469	215
8	40	41.6	1300	321	129	91.4	49	420	761	457	809	514	380
9	20	43.1	904	166	44.7	108	35.1	249	328	143	540	174	196
9	30	26.7	1300	259	59.9	129	31.6	344	409	241	862	280	283
9	40	84.6	1810	379	87	170	45.2	513	627	388	1290	503	378
10	20	39.9	931	203	33.1	74.7	29.2	268	269	185	479	110	152
10	30	55.1	907	182	47.7	137	49.8	340	454	217	802	274	262
10	40	45.8	1770	347	67	156	55.7	456	636	353	880	516	249

Subject no.	Weight	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
11	20	53	773	156	43	96	43	224	246	113	487	200	231
11	30	65	927	164	75	130	66	258	295	145	515	205	207
11	40	94.5	1350	224	95	159	80.3	321	550	196	681	387	270
12	20	57.8	979	168	61.1	68.3	45.9	199	274	156	400	177	157
12	30	71.4	1130	223	66.3	127.5	55.8	399	340	238	727	255	240
12	40	92.9	1420	272	108	129	64.8	422	431	284	892	306	319

Table H-2: Raw data of low back and shoulder joint loading in Session 2

Subject no.	Degree	Weight	Direction	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
1	5	20	1	79	1090	255	55	67	24	256	276	152	573	177	209
1	5	30	1	135	1935	438	65	74	39	225	263	196	697	279	339
1	5	40	1	171	2610	588	65	133	47	474	473	424	873	456	373
1	5	20	2	81	847	174	64	105	35	281	300	144	507	210	213
1	5	30	2	100	1210	266	58	101	40	399	468	269	962	335	335
1	5	40	2	144	1355	186	123	130	59	390	461	197	879	402	374
1	10	20	1	87	1080	264	38	69	45	321	334	161	741	281	323
1	10	30	1	133	2619	661	134	158	56	411	447	543	998	619	529
1	10	40	1	176	3890	953	172	242	70	856	748	671	1310	978	673
1	10	20	2	74	620	127	39	79	24	205	315	100	527	88	169
1	10	30	2	84	924	179	60	90	39	244	322	132	623	167	164
1	10	40	2	90	819	178	42	70	38	243	269	124	508	142	422
2	5	20	1	51	872	186	60	63	21	244	237	183	388	116	163
2	5	30	1	98	1680	391	73	82	29	488	447	316	861	185	383
2	5	40	1	125	1870	428	81	102	32	576	531	374	1030	220	461
2	5	20	2	36	785	156	43	71	24	188	184	108	337	130	145
2	5	30	2	70	1030	194	78	59	28	290	327	230	569	200	180
2	5	40	2	58	1060	201	139	113	53	300	301	241	590	132	233
2	10	20	1	86	1610	355	69	79	38	378	545	333	738	437	250
2	10	30	1	86	2330	535	184	152	49	714	769	560	1060	649	461
2	10	40	1	163	2900	673	229	194	66	911	985	703	1350	837	601

Subject no.	Degree	Weight	Direction	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
2	10	20	2	39	938	182	61	67	26	241	254	201	404	178	182
2	10	30	2	48	936	206	62	74	32	327	297	198	529	158	236
2	10	40	2	52	954	161	35	56	42	284	267	161	512	135	225
3	5	20	1	50	863	188	60	63	22	248	241	185	404	133	162
3	5	30	1	95	1670	390	72	80	30	492	450	316	688	307	248
3	5	40	1	116	1820	482	58	113	44	590	655	465	639	369	444
3	5	20	2	34	738	153	42	72	24	189	186	107	335	130	146
3	5	30	2	70	1030	194	77	58	28	295	332	232	569	202	180
3	5	40	2	58	1070	202	133	75	53	328	331	242	651	131	237
3	10	20	1	83	1525	367	65	59	36	367	595	215	589	538	214
3	10	30	1	88	2290	525	184	153	51	502	772	552	887	609	332
3	10	40	1	156	3294	836	191	171	50	633	1138	689	1289	674	489
3	10	20	2	39	936	181	61	67	27	245	256	201	405	179	183
3	10	30	2	49	933	205	60	74	33	332	302	200	530	158	237
3	10	40	2	53	954	161	34	54	42	290	274	162	519	137	227
4	5	20	1	46	1070	229	72	49	23	137	240	150	279	227	134
4	5	30	1	52	1270	250	125	90	40	244	449	217	577	485	225
4	5	40	1	118	1830	347	124	153	42	454	820	348	932	817	268
4	5	20	2	54	1050	185	96	83	21	279	306	256	497	248	127
4	5	30	2	54	1440	272	150	82	31	345	370	300	569	513	161
4	5	40	2	81	3320	378	197	171	65	466	468	384	763	537	356
4	10	20	1	53	1470	289	149	114	49	305	556	270	730	614	281
4	10	30	1	48	2440	508	252	133	27	438	851	354	1220	768	471
4	10	40	1	99	2920	671	262	180	42	590	1140	827	1281	956	636
4	10	20	2	45	984	179	73	68	23	228	222	177	384	160	192
4	10	30	2	60	987	228	65	70	30	292	250	180	499	143	226
4	10	40	2	63	1070	229	75	81	38	348	305	231	595	177	256
5	5	20	1	65	1460	361	100	101	21	289	375	284	420	341	216
5	5	30	1	73	1370	327	55	89	33	200	407	133	495	363	270
5	5	40	1	125	1310	366	49	131	32	206	455	310	903	422	337
5	5	20	2	93	1100	192	47	72	30	238	218	130	475	201	206
5	5	30	2	97	1630	322	80	59	37	201	229	135	501	203	208
5	5	40	2	87	1990	395	126	131	47	314	307	341	730	183	232

Subject no.	Degree	Weight	Direction	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
5	10	20	1	77	1220	306	79	110	53	436	438	350	805	595	292
5	10	30	1	110	1520	379	125	107	41	631	523	475	951	653	390
5	10	40	1	143	3700	921	196	214	60	1030	1017	708	1457	867	538
5	10	20	2	70	854	155	77	73	27	328	308	207	675	223	242
5	10	30	2	56	1040	193	109	130	42	342	403	209	758	275	354
5	10	40	2	77	1050	226	70	106	41	380	355	235	869	245	381
6	5	20	1	72	1240	264	60	115	37	322	375	230	584	294	230
6	5	30	1	57	938	252	34	56	45	232	324	183	374	209	288
6	5	40	1	113	2200	519	57	139	62	229	878	193	532	677	374
6	5	20	2	57	1030	231	54	93	41	338	331	214	678	352	233
6	5	30	2	93	1230	265	88	105	53	433	425	271	879	453	302
6	5	40	2	125	2140	488	198	143	81	514	816	344	549	450	411
6	10	20	1	72	1240	264	60	115	54	322	645	230	680	364	246
6	10	30	1	111	2460	623	171	145	55	359	702	430	784	555	450
6	10	40	1	140	3332	942	159	199	62	831	1127	609	1054	633	598
6	10	20	2	71	1030	241	37	61	46	388	353	242	669	207	242
6	10	30	2	66	1010	240	47	88	56	382	350	234	692	259	255
6	10	40	2	83	995	228	105	122	46	381	413	227	734	289	298
7	5	20	1	108	1370	362	94	66	31	198	290	142	448	262	179
7	5	30	1	82	1250	338	59	79	26	251	398	206	423	362	155
7	5	40	1	134	1420	254	61	169	32	443	253	354	563	208	199
7	5	20	2	49	819	145	30	67	27	185	184	112	375	190	153
7	5	30	2	108	1530	274	133	116	38	417	433	336	771	394	220
7	5	40	2	132	3000	617	187	160	55	641	1070	508	963	468	369
7	10	20	1	65	1460	362	79	131	51	428	430	347	787	272	223
7	10	30	1	130	3120	780	175	181	47	587	1060	505	1126	732	425
7	10	40	1	145	3710	922	203	245	58	1010	1290	874	1468	984	530
7	10	20	2	71	1090	200	79	95	32	279	294	223	708	152	199
7	10	30	2	98	1210	247	88	106	36	304	300	196	794	278	242
7	10	40	2	107	1160	227	50	107	45	390	378	242	852	161	353
8	5	20	1	46	1070	230	72	48	23	139	240	151	281	227	135
8	5	30	1	55	1470	290	150	113	49	308	555	273	734	615	282
8	5	40	1	118	1830	348	124	153	41	460	817	352	939	818	267

Subject no.	Degree	Weight	Direction	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
8	5	20	2	54	1050	184	97	82	21	282	308	257	493	250	129
8	5	30	2	54	1430	271	150	83	30	430	474	367	747	416	255
8	5	40	2	107	2546	373	218	156	54	587	769	394	904	565	443
8	10	20	1	36	1160	230	72	75	39	273	261	138	530	489	191
8	10	30	1	49	2440	507	251	132	27	440	849	357	1220	724	473
8	10	40	1	101	2900	668	260	205	43	1130	1140	829	1504	984	630
8	10	20	2	45	986	178	73	68	24	231	222	178	384	160	190
8	10	30	2	60	988	230	64	69	30	294	252	181	498	142	225
8	10	40	2	63	1070	229	75	81	38	348	305	231	595	177	256
9	5	20	1	40	1390	315	88	72	29	261	300	230	607	235	192
9	5	30	1	62	1550	383	52	60	30	277	286	206	635	159	185
9	5	40	1	100	2138	470	97	136	43	280	600	271	874	692	447
9	5	20	2	47	809	143	73	49	30	269	286	212	739	157	214
9	5	30	2	91	1530	277	165	99	34	277	283	186	830	277	248
9	5	40	2	115	2830	543	169	102	59	357	357	228	855	169	344
9	10	20	1	102	1390	352	55	109	49	442	500	195	594	339	233
9	10	30	1	63	2448	600	156	134	44	334	516	420	778	563	407
9	10	40	1	147	3333	816	184	161	54	767	927	601	1554	716	573
9	10	20	2	66	1100	204	31	62	27	202	198	129	420	149	138
9	10	30	2	94	1210	243	95	100	36	389	410	153	716	217	310
9	10	40	2	103	1170	230	109	86	52	375	412	258	1024	332	323
10	5	20	1	67	1472	286	59	67	30	330	486	350	665	233	276
10	5	30	1	108	1860	388	40	113	47	564	531	387	858	300	319
10	5	40	1	118	2020	456	43	166	47	660	634	470	1130	653	260
10	5	20	2	80	1380	298	116	112	36	435	450	367	785	272	232
10	5	30	2	63	2400	486	127	143	63	821	995	454	968	606	332
10	5	40	2	93	3043	499	193	192	71	957	1105	512	1110	662	656
10	10	20	1	93	2180	483	61	123	52	821	743	558	860	542	359
10	10	30	1	59	2520	444	180	178	59	1080	1250	595	1050	666	676
10	10	40	1	121	2820	899	150	201	85	1330	1520	889	1480	930	923
10	10	20	2	56	1730	341	105	122	43	517	600	377	919	407	294
10	10	30	2	40	1130	209	98	161	45	646	491	294	843	359	246
10	10	40	2	75	2900	579	133	139	61	706	904	434	1073	513	650

Subject no.	Degree	Weight	Direction	L5S1 ML	L5S1 PD	L5S1 AP	RSC ML	RSC IS	RSC AP	RAC ML	RAC IS	RAC AP	RGH DIS	RGH IS	RGH AP
11	5	20	1	57	1081	240	81	58	32	146	254	164	302	250	157
11	5	30	1	66	1304	264	129	94	44	248	467	235	591	499	239
11	5	40	1	130	1841	359	126	155	44	476	842	370	957	785	280
11	5	20	2	67	1053	198	109	87	25	283	309	259	510	261	140
11	5	30	2	65	1451	283	161	93	41	356	381	311	590	524	172
11	5	40	2	95	2981	393	205	133	70	476	478	394	748	552	371
11	10	20	1	71	1488	307	167	132	48	323	574	288	701	585	252
11	10	30	1	57	2469	517	261	138	52	447	860	363	1165	683	416
11	10	40	1	109	2930	690	281	187	61	910	920	607	1190	893	616
11	10	20	2	41	980	175	69	64	19	224	218	173	380	156	188
11	10	30	2	54	981	222	129	64	37	308	266	196	515	159	242
11	10	40	2	68	1125	234	80	86	43	353	318	244	608	190	269
12	5	20	1	65	937	199	69	76	27	261	266	204	417	136	184
12	5	30	1	117	1686	405	87	97	41	500	463	316	869	194	402
12	5	40	1	144	1893	446	99	115	44	594	549	388	1047	238	473
12	5	20	2	59	808	179	66	88	40	217	213	137	366	150	165
12	5	30	2	107	1077	231	115	76	45	307	348	251	590	229	209
12	5	40	2	79	1111	222	158	86	58	321	322	265	614	156	257
12	10	20	1	105	1800	374	98	92	57	396	563	351	756	456	269
12	10	30	1	116	2384	559	218	135	61	748	803	594	1064	658	470
12	10	40	1	172	2937	684	240	205	77	922	986	714	1350	848	612
12	10	20	2	48	977	191	70	76	35	250	263	210	433	187	199
12	10	30	2	55	973	213	69	91	41	342	312	213	544	173	251
12	10	40	2	63	995	172	46	67	53	295	278	172	535	158	248

APPENDIX I: ANOVA TABLES FOR MODEL 1

Table I-1: ANOVA tables for peak reaction forces acting at the L5S1 joint in three anatomical directions as a function of load weight

General Linear Model:

L5S1ML, L5S1PD, L5S1AP versus Subject, Weight

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Weight	fixed	3	20, 30, 40

Analysis of Variance for L5S1ML, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	28466.8	28466.8	2587.9	9.73	0.000
Weight	2	7098.5	7098.5	3549.3	13.35	0.000
Error	22	5850.2	5850.2	265.9		
Total	35	41415.6				

S = 16.3070 R-Sq = 85.87% R-Sq(adj) = 77.53%

Analysis of Variance for L5S1PD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	722376	722376	65671	3.55	0.006
Weight	2	1997981	1997981	998990	53.95	0.000
Error	22	407385	407385	18517		
Total	35	3127741				

S = 136.079 R-Sq = 86.98% R-Sq(adj) = 79.28%

Analysis of Variance for L5S1AP, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	177156	177156	16105	5.52	0.000
Weight	2	162488	162488	81244	27.82	0.000
Error	22	64242	64242	2920		
Total	35	403887				

S = 54.0380 R-Sq = 84.09% R-Sq(adj) = 74.69%

Table I-2: ANOVA tables for peak reaction forces acting at the sternoclavicular (SC) joint in three anatomical directions as a function of load weight

General Linear Model:

RSCML, RSCIS, RSCAP versus Subject, Weight

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

Weight	fixed	3	20, 30, 40				
Analysis of Variance for RSCML, using Adjusted SS for Tests							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Subject	11	15153.7	15153.7	1377.6	14.80	0.000	
Weight	2	4647.5	4647.5	2323.8	24.97	0.000	
Error	22	2047.4	2047.4	93.1			
Total	35	21848.6					
S = 9.64697 R-Sq = 90.63% R-Sq(adj) = 85.09%							
Analysis of Variance for RSCIS, using Adjusted SS for Tests							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Subject	11	13196.0	13196.0	1199.6	7.77	0.000	
Weight	2	21725.8	21725.8	10862.9	70.40	0.000	
Error	22	3394.7	3394.7	154.3			
Total	35	38316.4					
S = 12.4219 R-Sq = 91.14% R-Sq(adj) = 85.91%							
Analysis of Variance for RSCAP, using Adjusted SS for Tests							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Subject	11	4136.50	4136.50	376.05	12.39	0.000	
Weight	2	1890.83	1890.83	945.41	31.15	0.000	
Error	22	667.70	667.70	30.35			
Total	35	6695.03					
S = 5.50908 R-Sq = 90.03% R-Sq(adj) = 84.13%							

Table I-3: ANOVA tables for peak reaction forces acting at the acromioclavicular (AC) joint in three anatomical directions as a function of load weight

General Linear Model:							
RACML, RACIS, RACAP versus Subject, Weight							
Factor	Type	Levels	Values				
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12				
Weight	fixed	3	20, 30, 40				
Analysis of Variance for RACML, using Adjusted SS for Tests							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Subject	11	99282	99282	9026	5.46	0.000	
Weight	2	240929	240929	120464	72.90	0.000	
Error	22	36355	36355	1652			
Total	35	376565					
S = 40.6508 R-Sq = 90.35% R-Sq(adj) = 84.64%							

Analysis of Variance for RACIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	219546	219546	19959	9.13	0.000
Weight	2	456162	456162	228081	104.28	0.000
Error	22	48119	48119	2187		
Total	35	723828				
S = 46.7678 R-Sq = 93.35% R-Sq(adj) = 89.42%						

Analysis of Variance for RACAP, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	129343	129343	11758	6.36	0.000
Weight	2	152308	152308	76154	41.22	0.000
Error	22	40644	40644	1847		
Total	35	322294				
S = 42.9819 R-Sq = 87.39% R-Sq(adj) = 79.94%						

Table I-4: ANOVA tables for peak reaction forces acting at the glenohumeral (GH) joint in three anatomical directions as a function of load weight

General Linear Model:

RGHDIS, RGHIS, RGHAP versus Subject, Weight

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Weight	fixed	3	20, 30, 40

Analysis of Variance for RGHDIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	254460	254460	23133	7.27	0.000
Weight	2	689811	689811	344906	108.37	0.000
Error	22	70018	70018	3183		
Total	35	1014289				
S = 56.4147 R-Sq = 93.10% R-Sq(adj) = 89.02%						

Analysis of Variance for RGHIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	398705	398705	36246	5.33	0.000
Weight	2	325298	325298	162649	23.93	0.000
Error	22	149552	149552	6798		
Total	35	873555				
S = 82.4489 R-Sq = 82.88% R-Sq(adj) = 72.76%						

Analysis of Variance for RGHAP, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	155865	155865	14170	6.89	0.000
Weight	2	135534	135534	67767	32.94	0.000
Error	22	45263	45263	2057		
Total	35	336662				
S = 45.3587 R-Sq = 86.56% R-Sq(adj) = 78.61%						

APPENDIX J: ANOVA TABLES FOR MODEL 2

Table J-1: ANOVA tables for peak reaction forces acting at the L5S1 joint in three anatomical directions as a function of walkway gradient, load weight, and direction of force application

General Linear Model:

L5S1ML, L5S1PD, L5S1AP versus Subject, Degree, Weight, Direction

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Degree	fixed	2	5, 10
Weight	fixed	3	20, 30, 40
Direction	fixed	2	1, 2

Analysis of Variance for L5S1ML, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	28143.0	28143.0	2558.5	8.40	0.000
Degree	1	126.7	126.7	126.7	0.42	0.520
Weight	2	52393.5	52393.5	26196.7	85.99	0.000
Direction	1	20805.9	20805.9	20805.9	68.29	0.000
Degree*Weight	2	1070.1	1070.1	535.0	1.76	0.177
Degree*Direction	1	5937.9	5937.9	5937.9	19.49	0.000
Weight*Direction	2	9041.5	9041.5	4520.8	14.84	0.000
Degree*Weight*Direction	2	530.6	530.6	265.3	0.87	0.421
Error	121	36863.5	36863.5	304.7		
Total	143	154912.7				

S = 17.4544 R-Sq = 76.20% R-Sq(adj) = 71.88%

Analysis of Variance for L5S1PD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	4883091	4883091	443917	3.34	0.000
Degree	1	1471189	1471189	1471189	11.06	0.001
Weight	2	23013084	23013084	11506542	86.52	0.000
Direction	1	14884621	14884621	14884621	111.92	0.000
Degree*Weight	2	80158	80158	40079	0.30	0.740
Degree*Direction	1	15172901	15172901	15172901	114.08	0.000
Weight*Direction	2	1894855	1894855	947427	7.12	0.001
Degree*Weight*Direction	2	6571397	6571397	3285699	24.70	0.000
Error	121	16092892	16092892	132999		
Total	143	84064188				

S = 364.690 R-Sq = 80.86% R-Sq(adj) = 77.38%

Analysis of Variance for L5S1AP, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	242687	242687	22062	3.53	0.000
Degree	1	227602	227602	227602	36.44	0.000
Weight	2	1133253	1133253	566626	90.72	0.000
Direction	1	1493834	1493834	1493834	239.18	0.000
Degree*Weight	2	42633	42633	21317	3.41	0.036
Degree*Direction	1	725152	725152	725152	116.10	0.000
Weight*Direction	2	251423	251423	125711	20.13	0.000
Degree*Weight*Direction	2	319680	319680	159840	25.59	0.000
Error	121	755738	755738	6246		
Total	143	5192002				
S = 79.0302 R-Sq = 85.44% R-Sq(adj) = 82.80%						

Table J-2: ANOVA tables for peak reaction forces acting at the sternoclavicular (SC) joint in three anatomical directions as a function of walkway gradient, load weight, and direction of force application

General Linear Model:

RSCML, RSCIS, RSCAP versus Subject, Degree, Weight, Direction

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Degree	fixed	2	5, 10
Weight	fixed	3	20, 30, 40
Direction	fixed	2	1, 2

Analysis of Variance for RSCML, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	66964	66964	6088	9.17	0.000
Degree	1	12259	12259	12259	18.47	0.000
Weight	2	95387	95387	47693	71.85	0.000
Direction	1	21584	21584	21584	32.52	0.000
Degree*Weight	2	7843	7843	3921	5.91	0.004
Degree*Direction	1	154122	154122	154122	232.17	0.000
Weight*Direction	2	4465	4465	2233	3.36	0.038
Degree*Weight*Direction	2	69332	69332	34666	52.22	0.000
Error	121	80322	80322	664		
Total	143	512277				

S = 25.7646 R-Sq = 84.32% R-Sq(adj) = 81.47%

Analysis of Variance for RSCIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	30248	30248	2750	7.48	0.000

Degree	1	10817	10817	10817	29.43	0.000
Weight	2	82436	82436	41218	112.13	0.000
Direction	1	32733	32733	32733	89.05	0.000
Degree*Weight	2	3789	3789	1894	5.15	0.007
Degree*Direction	1	39828	39828	39828	108.35	0.000
Weight*Direction	2	17033	17033	8517	23.17	0.000
Degree*Weight*Direction	2	7707	7707	3854	10.48	0.000
Error	121	44477	44477	368		
Total	143	269068				
S = 19.1724 R-Sq = 83.47% R-Sq(adj) = 80.46%						
Analysis of Variance for RSCAP, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	5418.73	5418.73	492.61	12.93	0.000
Degree	1	1030.09	1030.09	1030.09	27.05	0.000
Weight	2	8674.87	8674.87	4337.43	113.89	0.000
Direction	1	464.91	464.91	464.91	12.21	0.001
Degree*Weight	2	521.01	521.01	260.50	6.84	0.002
Degree*Direction	1	4311.24	4311.24	4311.24	113.20	0.000
Weight*Direction	2	470.34	470.34	235.17	6.17	0.003
Degree*Weight*Direction	2	796.83	796.83	398.41	10.46	0.000
Error	121	4608.41	4608.41	38.09		
Total	143	26296.41				
S = 6.17138 R-Sq = 82.48% R-Sq(adj) = 79.29%						

Table J-3: ANOVA tables for peak reaction forces acting at the acromioclavicular (AC) joint in three anatomical directions as a function of walkway gradient, load weight, and direction of force application

General Linear Model:			
RACML, RACIS, RACAP versus Subject, Degree, Weight, Direction			
Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Degree	fixed	2	5, 10
Weight	fixed	3	20, 30, 40
Direction	fixed	2	1, 2
Analysis of Variance for RACML, using Adjusted SS for Tests			
Source	DF	Seq SS	Adj SS Adj MS F P
Subject	11	1460170	1460170 132743 12.56 0.000
Degree	1	519303	519303 519303 49.12 0.000
Weight	2	1569472	1569472 784736 74.23 0.000
Direction	1	611852	611852 611852 57.88 0.000

Degree*Weight	2	56165	56165	28082	2.66	0.074
Degree*Direction	1	933365	933365	933365	88.29	0.000
Weight*Direction	2	324947	324947	162473	15.37	0.000
Degree*Weight*Direction	2	272758	272758	136379	12.90	0.000
Error	121	1279113	1279113	10571		
Total	143	7027144				
S = 102.816 R-Sq = 81.80% R-Sq(adj) = 78.49%						
Analysis of Variance for RACIS, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	1615380	1615380	146853	8.43	0.000
Degree	1	588781	588781	588781	33.80	0.000
Weight	2	2401812	2401812	1200906	68.94	0.000
Direction	1	2148728	2148728	2148728	123.36	0.000
Degree*Weight	2	1938	1938	969	0.06	0.946
Degree*Direction	1	1686758	1686758	1686758	96.84	0.000
Weight*Direction	2	405921	405921	202961	11.65	0.000
Degree*Weight*Direction	2	301879	301879	150940	8.67	0.000
Error	121	2107655	2107655	17419		
Total	143	11258853				
S = 131.980 R-Sq = 81.28% R-Sq(adj) = 77.88%						
Analysis of Variance for RACAP, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	411329	411329	37394	8.66	0.000
Degree	1	250608	250608	250608	58.06	0.000
Weight	2	894930	894930	447465	103.67	0.000
Direction	1	753177	753177	753177	174.49	0.000
Degree*Weight	2	40678	40678	20339	4.71	0.011
Degree*Direction	1	743428	743428	743428	172.23	0.000
Weight*Direction	2	280930	280930	140465	32.54	0.000
Degree*Weight*Direction	2	245806	245806	122903	28.47	0.000
Error	121	522290	522290	4316		
Total	143	4143175				
S = 65.6996 R-Sq = 87.39% R-Sq(adj) = 85.10%						

Table J-4: ANOVA tables for peak reaction forces acting at the glenohumeral (GH) joint in three anatomical directions as a function of walkway gradient, load weight, and direction of force application

General Linear Model:

RGHDIS, RGHIS, RGHAP versus Subject, Degree, Weight, Direction

Factor	Type	Levels	Values
Subject	random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

Degree	fixed	2	5, 10
Weight	fixed	3	20, 30, 40
Direction	fixed	2	1, 2

Analysis of Variance for RGHDIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	1033311	1033311	93937	4.92	0.000
Degree	1	964872	964872	964872	50.53	0.000
Weight	2	3460671	3460671	1730335	90.62	0.000
Direction	1	1444113	1444113	1444113	75.63	0.000
Degree*Weight	2	31925	31925	15963	0.84	0.436
Degree*Direction	1	1612293	1612293	1612293	84.44	0.000
Weight*Direction	2	598004	598004	299002	15.66	0.000
Degree*Weight*Direction	2	161621	161621	80810	4.23	0.017
Error	121	2310372	2310372	19094		
Total	143	11617181				

S = 138.181 R-Sq = 80.11% R-Sq(adj) = 76.50%

Analysis of Variance for RGHIS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	791083	791083	71917	6.02	0.000
Degree	1	323758	323758	323758	27.11	0.000
Weight	2	1211743	1211743	605872	50.74	0.000
Direction	1	2233523	2233523	2233523	187.05	0.000
Degree*Weight	2	3010	3010	1505	0.13	0.882
Degree*Direction	1	1494048	1494048	1494048	125.12	0.000
Weight*Direction	2	436542	436542	218271	18.28	0.000
Degree*Weight*Direction	2	90721	90721	45360	3.80	0.025
Error	121	1444825	1444825	11941		
Total	143	8029253				

S = 109.274 R-Sq = 82.01% R-Sq(adj) = 78.73%

Analysis of Variance for RGHAP, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	11	289281	289281	26298	5.93	0.000
Degree	1	286509	286509	286509	64.66	0.000
Weight	2	1021979	1021979	510989	115.32	0.000
Direction	1	370554	370554	370554	83.62	0.000
Degree*Weight	2	29741	29741	14870	3.36	0.038
Degree*Direction	1	264450	264450	264450	59.68	0.000
Weight*Direction	2	79997	79997	39998	9.03	0.000
Degree*Weight*Direction	2	95816	95816	47908	10.81	0.000
Error	121	536174	536174	4431		
Total	143	2974499				

S = 66.5672 R-Sq = 81.97% R-Sq(adj) = 78.70%

**APPENDIX K: ALL-PAIRWISE COMPARISON TEST TABLES FOR
MODEL 2**

Table K-1: Tukey HSD All-pairwise comparisons test for averaged peak L5S1-ML forces for different walkway gradient, load weight and direction of force application along ramps
An asterisk (*) represents a significant difference

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	62.1											
5°	20 kg	2-down	59.2	-2.9										
5°	30 kg	1-up	83.3	21.2	24.1*									
5°	30 kg	2-down	80.8	18.7	21.6	-2.5								
5°	40 kg	1-up	126.0	63.9*	66.8*	42.7*	45.2*							
5°	40 kg	2-down	97.8	35.7*	38.6*	14.5	17.0	-28.2*						
10°	20 kg	1-up	77.6	15.5	18.4	-5.7	-3.2	-48.4*	-20.2					
10°	20 kg	2-down	55.4	-6.7	-3.8	-27.9*	-25.4*	-70.6*	-42.4*	-22.2				
10°	30 kg	1-up	87.5	25.4*	28.3*	4.2	6.7	-38.5*	-10.3	9.9	32.1*			
10°	30 kg	2-down	63.7	1.6	4.5	-19.6	-17.1	-62.3*	-34.1*	-13.9	8.3	-23.8*		
10°	40 kg	1-up	139.3	77.2*	80.1*	56.0*	58.5*	13.3	41.5*	61.7*	83.9*	51.8*	75.6*	
10°	40 kg	2-down	74.6	12.5	15.4	-8.7	-6.2	-51.4*	-23.2	-3.0	19.2	-12.9	10.9	-64.7*

Table K-2: Tukey HSD All-pairwise comparisons test for averaged peak L5S1-PD forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	1159.6											
5°	20 kg	2-down	955.8	-204										
5°	30 kg	1-up	1498.6	339	543*									
5°	30 kg	2-down	1415.7	256	460	-83								
5°	40 kg	1-up	1898.5	739*	943*	400	483							
5°	40 kg	2-down	2203.8	1044*	1248*	705*	788*	305						
10°	20 kg	1-up	1468.6	309	513*	-30	53	-430	-735*					
10°	20 kg	2-down	1018.8	-141	63	-480	-397	-879*	-1185*	-450				
10°	30 kg	1-up	2420.0	1260*	1464*	921*	1004*	521.5*	216	951*	1401*			
10°	30 kg	2-down	1026.8	-133	71	-472	-389	-871*	-1177*	-442	8	-1393*		
10°	40 kg	1-up	3222.1	2062*	2266*	1723*	1806*	1323*	1018*	1753*	2203*	802*	2195*	
10°	40 kg	2-down	1188.5	29	233	-310	-227	-710*	-1015*	-280	170	-1231*	162	-2033*

Table K-3: Tukey HSD All-pairwise comparisons test for averaged peak L5S1-AP forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	259.6											
5°	20 kg	2-down	186.5	-73.1										
5°	30 kg	1-up	343.0	83.4	156.5*									
5°	30 kg	2-down	277.9	18.3	91.4	-65.1								
5°	40 kg	1-up	421.9	162.3*	235.4*	78.9	144.0*							
5°	40 kg	2-down	374.7	115.1*	188.2*	31.7	96.8	-47.2						
10°	20 kg	1-up	329.4	69.8	142.9*	-13.6	51.5	-92.5	-45.3					
10°	20 kg	2-down	196.2	-63.4	9.7	-146.8*	-81.7	-225.7*	-178.5*	-133.2*				
10°	30 kg	1-up	553.2	293.6*	366.7*	210.2*	275.3*	131.3*	178.5*	223.8*	357.0*			
10°	30 kg	2-down	217.9	-41.7	31.4	-125.1*	-60.0	-204.0*	-156.8*	-111.5*	21.7	-335.3*		
10°	40 kg	1-up	806.2	546.6*	619.7*	463.2*	528.3*	384.3*	431.5*	476.8*	610.0*	253.0*	588.3*	
10°	40 kg	2-down	237.8	-21.8	51.3	-105.2	-40.1	-184.1*	-136.9*	-91.6	41.6	-315.4*	19.9	-568.4*

Table K-4: Tukey HSD All-pairwise comparisons test for averaged peak RSC-ML forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	72.4											
5°	20 kg	2-down	69.7	-2.7										
5°	30 kg	1-up	78.2	5.8	8.5									
5°	30 kg	2-down	115.2	42.8*	45.5*	37.0*								
5°	40 kg	1-up	81.9	9.5	12.2	3.7	-33.3							
5°	40 kg	2-down	170.5	98.1*	100.8*	92.3*	55.3*	88.6*						
10°	20 kg	1-up	82.6	10.2	12.9	4.4	-32.6	0.7	-87.9*					
10°	20 kg	2-down	64.5	-7.9	-5.2	-13.7	-50.7*	-17.4	-106*	-18.1				
10°	30 kg	1-up	190.9	118.5*	121.2*	112.7*	75.7*	109.0*	20.4	108.3*	126.4*			
10°	30 kg	2-down	78.7	6.3	9.0	0.5	-36.5*	-3.2	-91.8*	-3.9	14.2	-112.2*		
10°	40 kg	1-up	210.6	138.2*	140.9*	132.4*	95.4*	128.7*	40.1*	128.0*	146.1*	19.7	131.9*	
10°	40 kg	2-down	71.2	-1.2	1.5	-7.0	-44.0*	-10.7	-99.3*	-11.4	6.7	-119.7*	-7.5	-139.4*

Table K-5: Tukey HSD All-pairwise comparisons test for averaged peak RSC-IS forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	70.3											
5°	20 kg	2-down	81.8	11.5										
5°	30 kg	1-up	85.6	15.3	3.8									
5°	30 kg	2-down	89.5	19.2	7.7	3.9								
5°	40 kg	1-up	138.8	68.5*	57.0*	53.2*	49.3*							
5°	40 kg	2-down	132.7	62.4*	50.9*	47.1*	43.2*	-6.1						
10°	20 kg	1-up	100.6	30.3*	18.8	15.0	11.1	-38.2*	-32.1*					
10°	20 kg	2-down	75.3	5.0	-6.5	-10.3	-14.2	-63.5*	-57.4*	-25.3				
10°	30 kg	1-up	145.5	75.2*	63.7*	59.9*	56.0*	6.7	12.8	44.9*	70.2*			
10°	30 kg	2-down	93.0	22.7	11.2	7.4	3.5	-45.8*	-39.7*	-7.6	17.7	-52.5*		
10°	40 kg	1-up	200.3	130*	118.5*	114.7*	110.8*	61.5*	67.6*	99.7*	125.0*	54.8*	107.3*	
10°	40 kg	2-down	87.9	17.6	6.1	2.3	-1.6	-50.9*	-44.8*	-12.7	12.6	-57.6*	-5.1	-112.4*

Table K-6: Tukey HSD All-pairwise comparisons test for averaged peak RSC-AP forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	26.6											
5°	20 kg	2-down	29.4	2.8										
5°	30 kg	1-up	37.7	11.1*	8.3									
5°	30 kg	2-down	38.9	12.3*	9.5*	1.2								
5°	40 kg	1-up	42.4	15.8*	13.0*	4.7	3.5							
5°	40 kg	2-down	60.5	33.9*	31.1*	22.8*	21.6*	18.1*						
10°	20 kg	1-up	47.5	20.9*	18.1*	9.8*	8.6*	5.1	-13.0*					
10°	20 kg	2-down	29.3	2.7	-0.1	-8.4	-9.6*	-13.1*	-31.2*	-18.2*				
10°	30 kg	1-up	47.5	20.9*	18.1*	9.8*	8.6*	5.1	-13.0*	0.0	18.2*			
10°	30 kg	2-down	37.9	11.3*	8.5*	0.2	-1.0	-4.5	-22.6*	-9.6*	8.6*	-9.6*		
10°	40 kg	1-up	60.6	34.0*	31.2*	22.9*	21.7*	18.2*	0.1	13.1*	31.3*	13.1*	22.7*	
10°	40 kg	2-down	44.8	18.2*	15.4*	7.1	5.9	2.4	-15.7*	-2.7	15.5*	-2.7	6.9	-15.8*

Table K-7: Tukey HSD All-pairwise comparisons test for averaged peak RAC-ML forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	235.9											
5°	20 kg	2-down	265.3	29.4										
5°	30 kg	1-up	335.8	99.9	70.5									
5°	30 kg	2-down	380.9	145.0*	115.6	45.1								
5°	40 kg	1-up	453.5	217.6*	188.2*	117.7	72.6							
5°	40 kg	2-down	470.9	235.0*	205.6*	135.1	90.0	17.4						
10°	20 kg	1-up	401.0	165.1*	135.7	65.2	20.1	-52.5	-69.9					
10°	20 kg	2-down	278.2	42.3	12.9	-57.6	-102.7	-175*	-193*	-122.8				
10°	30 kg	1-up	557.6	321.7*	292.3*	221.8*	176.7*	104.1	86.7	156.6*	279.4*			
10°	30 kg	2-down	350.2	114.3	84.9	14.4	-30.7	-103.3	-120.7	-50.8	72.0	-207.4*		
10°	40 kg	1-up	910.0	674.1*	644.7*	574.2*	529.1*	456.5*	439.1*	509.0*	631.8*	352.4*	559.8*	
10°	40 kg	2-down	366.1	130.2	100.8	30.3	-14.8	-87.4	-104.8	-34.9	87.9	-191.5*	15.9	-543.9*

Table K-8: Tukey HSD All-pairwise comparisons test for averaged peak RAC-IS forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	298.4											
5°	20 kg	2-down	272.9	-25.5										
5°	30 kg	1-up	420.0	121.6	147.1									
5°	30 kg	2-down	422.1	123.7	149.2	2.1								
5°	40 kg	1-up	625.6	327.2*	352.7*	205.6*	203.5*							
5°	40 kg	2-down	565.4	267.0*	292.5*	145.4	143.3	-60.2						
10°	20 kg	1-up	515.3	216.9*	242.4*	95.3	93.2	-110.3	-50.1					
10°	20 kg	2-down	291.9	-6.5	19.0	-128.1	-130.2	-333.7*	-273.5*	-223.4*				
10°	30 kg	1-up	783.5	485.1*	510.6*	363.5*	361.4*	157.9	218.1*	268.2*	491.6*			
10°	30 kg	2-down	329.6	31.2	56.7	-90.4	-92.5	-296.0*	-235.8*	-185.7*	37.7	-453.9*		
10°	40 kg	1-up	1078	779.7*	805.2*	658.1*	656.0*	452.5*	512.7*	562.8*	786.2*	294.6*	748.5*	
10°	40 kg	2-down	373.2	74.8	100.3	-46.8	-48.9	-252.4*	-192.2*	-142.1	81.3	-410.3*	43.6	-704.9*

Table K-9: Tukey HSD All-pairwise comparisons test for averaged peak RAC-AP forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	202.1											
5°	20 kg	2-down	191.9	-10.2										
5°	30 kg	1-up	248.7	46.6	56.8									
5°	30 kg	2-down	278.5	76.4	86.6	29.8								
5°	40 kg	1-up	360.0	157.9*	168.1*	111.3*	81.5							
5°	40 kg	2-down	337.5	135.4*	145.6*	88.8	59.0	-22.5						
10°	20 kg	1-up	286.3	84.2	94.4*	37.6	7.8	-73.7	-51.2					
10°	20 kg	2-down	201.5	-0.6	9.6	-47.2	-77.0	-158.5*	-136.0*	-84.8				
10°	30 kg	1-up	479.0	276.9*	287.1*	230.3*	200.5*	119.0*	141.5*	192.7*	277.5*			
10°	30 kg	2-down	198.8	-3.3	6.9	-49.9	-79.7	-161.2*	-138.7*	-87.5	-2.7	-280.2*		
10°	40 kg	1-up	726.8	524.7*	534.9*	478.1*	448.3*	366.8*	389.3*	440.5*	525.3*	247.8*	528.0*	
10°	40 kg	2-down	226.8	24.7	34.9	-21.9	-51.7	-133.2*	-110.7*	-59.5	25.3	-252.2*	28.0	-500.0*

Table K-10: Tukey HSD All-pairwise comparisons test for averaged peak RGH-DIS forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	447.4											
5°	20 kg	2-down	508.1	60.7										
5°	30 kg	1-up	650.2	202.8*	142.1									
5°	30 kg	2-down	712.1	264.7*	204.0*	61.9								
5°	40 kg	1-up	868.3	420.9*	360.2*	218.1*	156.2							
5°	40 kg	2-down	779.7	332.3*	271.6*	129.5	67.6	-88.6						
10°	20 kg	1-up	709.2	261.8*	201.1*	59.0	-2.9	-159.1	-70.5					
10°	20 kg	2-down	525.7	78.3	17.6	-124.5	-186.4	-343*	-254*	-183.5				
10°	30 kg	1-up	1025.2	577.8*	517.1*	375.0*	313.1*	156.9	245.5*	316.0*	499.5*			
10°	30 kg	2-down	628.4	181.0	120.3	-21.8	-83.7	-240*	-151.3	-80.8	102.7	-396.8*		
10°	40 kg	1-up	1357.3	909.9*	849.2*	707.1*	645.2*	489.0*	577.6*	648.1*	831.6*	332.1*	728.9*	
10°	40 kg	2-down	702.0	254.6*	193.9*	51.8	-10.1	-166.3	-77.7	-7.2	176.3	-323.2*	73.6	-655.3*

Table K-11: Tukey HSD All-pairwise comparisons test for averaged peak RGH-IS forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	219.2											
5°	20 kg	2-down	212.6	-6.6										
5°	30 kg	1-up	329.8	110.6	117.2									
5°	30 kg	2-down	362.7	143.5	150.1*	32.9								
5°	40 kg	1-up	529.6	310.4*	317.0*	199.8*	166.9*							
5°	40 kg	2-down	367.2	148.0	154.6*	37.4	4.5	-162.4*						
10°	20 kg	1-up	459.3	240.1*	246.7*	129.5	96.6	-70.3	92.1					
10°	20 kg	2-down	187.2	-32.0	-25.4	-142.6	-175.5*	-342.4*	-180.0*	-272.1*				
10°	30 kg	1-up	656.6	437.4*	444.0*	326.8*	293.9*	127.0	289.4*	197.3*	469.4*			
10°	30 kg	2-down	207.3	-11.9	-5.3	-122.5	-155.4*	-322.3*	-159.9*	-252.0*	20.1	-449.3*		
10°	40 kg	1-up	858.3	639.1*	645.7*	528.5*	495.6*	328.7*	491.1*	399.0*	671.1*	201.7*	651.0*	
10°	40 kg	2-down	221.3	2.1	8.7	-108.5	-141.4	-308.3*	-145.9	-238.0*	34.1	-435.3*	14.0	-637.0*

Table K-12: Tukey HSD All-pairwise comparisons test for averaged peak RGH-AP forces for different walkway gradient, load weight and direction of force application along ramps

Degree	Weight	Direction	Mean	5,20,1	5,20,2	5,30,1	5,30,2	5,40,1	5,40,2	10,20,1	10,20,2	10,30,1	10,30,2	10,40,1
5°	20 kg	1-up	186.4											
5°	20 kg	2-down	175.3	-11.1										
5°	30 kg	1-up	277.9	91.5*	102.6*									
5°	30 kg	2-down	233.5	47.1	58.2	-44.4								
5°	40 kg	1-up	348.6	162.2*	173.3*	70.7	115.1*							
5°	40 kg	2-down	356.9	170.5*	181.6*	79.0	123.4*	8.3						
10°	20 kg	1-up	261.1	74.7	85.8	-16.8	27.6	-87.5	-95.8*					
10°	20 kg	2-down	201.5	15.1	26.2	-76.4	-32.0	-147.1*	-155.4*	-59.6				
10°	30 kg	1-up	458.3	271.9*	283.0*	180.4*	224.8*	109.7*	101.4*	197.2*	256.8*			
10°	30 kg	2-down	249.0	62.6	73.7	-28.9	15.5	-99.6*	-107.9*	-12.1	47.5	-209.3*		
10°	40 kg	1-up	618.2	431.8*	442.9*	340.3*	384.7*	269.6*	261.3*	357.1*	416.7*	159.9*	369.2*	
10°	40 kg	2-down	325.7	139.3*	150.4*	47.8	92.2*	-22.9	-31.2	64.6	124.2*	-132.6*	76.7	-292.5*

APPENDIX L: REGRESSION ANALYSIS FOR PROBLEMATIC LOADING

Table L-1: Regression analysis for peak reaction forces acting at the L5S1 joint in anterior-posterior (AP) directions during uphill pushing depending on walkway gradient and load weight

Regression Analysis: L5S1AP versus Degree, Weight, Degree*Weight

The regression equation is

$$\text{L5S1AP} = 57.6 - 15.2 \text{ Degree} + 5.45 \text{ Weight} + 1.58 \text{ Degree*Weight}$$

Predictor	Coef	SE Coef	T	P
Constant	57.64	55.21	1.04	0.299
Degree	-15.178	8.554	-1.77	0.079
Weight	5.451	1.776	3.07	0.003
Degree*Weight	1.5777	0.2751	5.73	0.000

S = 95.3025 R-Sq = 78.5% R-Sq(adj) = 77.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	3441009	1147003	126.29	0.000
Residual Error	104	944587	9083		
Total	107	4385597			

Table L-2: Regression analysis for peak reaction forces acting at the acromioclavicular (AC) joint in inferior-superior (IS) direction during uphill pushing depending on walkway gradient and load weight

Regression Analysis: RACIS versus Degree, Weight, Degree*Weight

The regression equation is

$$\text{RACIS} = -59.9 + 1.3 \text{ Degree} + 14.3 \text{ Weight} + 1.19 \text{ Degree*Weight}$$

Predictor	Coef	SE Coef	T	P
Constant	-59.89	96.52	-0.62	0.536
Degree	1.32	14.95	0.09	0.930
Weight	14.323	3.104	4.61	0.000
Degree*Weight	1.1870	0.4809	2.47	0.015

S = 166.602 R-Sq = 65.9% R-Sq(adj) = 64.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	5578549	1859516	66.99	0.000
Residual Error	104	2886640	27756		
Total	107	8465189			

Table L-3: Regression analysis for peak reaction forces acting at the glenohumeral joint (GH) in distraction (DIS) direction during uphill pushing depending on walkway gradient and load weight

Regression Analysis: RGHDIS versus Degree, Weight, Degree*Weight

The regression equation is

$$\text{RGHDIS} = 10 + 4.4 \text{ Degree} + 19.8 \text{ Weight} + 1.06 \text{ Degree*Weight}$$

Predictor	Coef	SE Coef	T	P
Constant	10.5	101.3	0.10	0.918
Degree	4.38	15.69	0.28	0.781
Weight	19.792	3.257	6.08	0.000
Degree*Weight	1.0592	0.5045	2.10	0.038

S = 174.768 R-Sq = 68.8% R-Sq(adj) = 67.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	7018844	2339615	76.60	0.000
Residual Error	104	3176577	30544		
Total	107	10195422			