Preventing Back Injury in Caregivers

by

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Abstract

Caregivers injure their backs more than workers in any other industry. Efforts to reduce injuries have been on-going for decades with limited results. Mechanical lift devices have been incorporated into clinical practice over the past 30 years to reduce the risk of injury from patient lifting. Yet injury rates remain high. The use of mechanical lifts may be partly to blame. While these devices assist with lifting patients, they also introduce new activities that result in caregivers experiencing unsafe loading on the spine.

We measured loads on the lower back during manoeuvres of the two most common lift types (overhead and floor) as well as during sling insertion. A new device called SlingSerter™ was evaluated for use in the clinical environment. We also investigated spine shrinkage as a measurement tool for estimating cumulative load.
Caregivers worked alone and in pairs for both lift maneuvering and sling insertion activities. Overhead lift use resulted in much lower loads than floor lift use. We conclude caregivers can safely operate overhead lifts alone, while floor lift use remained unsafe even with two caregivers. Less-experienced caregivers had higher loads than more-experienced counterparts when using floor lifts. There was no corresponding effect of experience with overhead lift use and we found this to be a further benefit of overhead lifts over floor lifts. Most caregivers exceeded the safe limit for spine compression during sling insertion, though a single caregiver was at no higher risk of injury than two caregivers working together.

Clinicians who tested SlingSerture™ agreed the device would be useful in clinical practice, particularly with bariatric patients and other special patient populations that are difficult to roll or turn. Finally, we investigated a novel method for estimating cumulative load based on spine shrinkage. There is growing recognition that excess cumulative load may be responsible for back injury. We found the variability in spine shrinkage was too large to estimate cumulative load directly. However, the technique may still be useful for determining the relative importance of the load from different activities to the cumulative total.
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1 Caregivers and Back Injury

We ask too much of our caregivers. These workers place themselves at high risk of back injury as they work to restore the health of their patients. Attempts to reduce the risk of harm to caregivers have been on-going for decades yet injury rates remain high. In this chapter, we look at the scope of this problem along with previous attempts to address back injury in the clinical environment.

We begin by reviewing the problem of back injury and back pain in section 1.1. Section 1.2 looks at the anatomy of the back, how it works and what can go wrong. Section 1.3 examines how patient lifting is done today and how it has changed over the years. We then analyze the most common methods used to evaluate the risk of injury during lifting activities in section 1.4 followed by a deeper look at biomechanical measurements in section 1.5. Section 1.6 reflects on environmental factors that surround caregiving such as work load and policy issues. Finally, section 1.7 summarizes the most likely causes of the high rates of back injury among caregivers today.

Terminology

In this work the term caregiver is used to represent a broad range of healthcare workers including registered nurses, licensed practical nurses, as well as nursing aides and orderlies. Similarly the term patient used here could be replaced with resident or client depending on context. Patients are found in the hospital setting while residents are cared for in nursing homes and clients at home.
1.1 Musculoskeletal Injuries in Caregivers

![Incidence rates of nonfatal injuries by industry](image)

The caregiver workforce consistently reports the highest rates of musculoskeletal injuries in any industry [1]. Caregivers are injured more than workers in mining, construction or manufacturing as shown in Figure 1 [2]. The incidents rate for musculoskeletal injuries in nursing aids, orderlies and attendants is 249.4 per 10,000 workers compared to 34.3 (per 10,000 workers) for all workers. Back injuries make up the majority of the injuries in caregivers (55.7%) while the average percentage of back injury for all occupations is lower (45.4%). Therefore, caregivers are nearly nine times more likely to experience a back injury compared to the average worker. Caregivers experience back injury at the rate of 138.9 per 10,000 caregivers compared to a rate of 15.6 for all workers [3]. This is particularly worrisome since back injuries result in the most lost work days per injury [4-6] and disproportionately higher compensations costs compared to other injuries [7].

There are even more caregivers that report back pain than those reporting injury. In a Canadian survey, 37% of caregivers had experienced pain serious enough to prevent them from carrying out their normal daily activities in the past year and one in ten reported severe or unbearable pain. In particular, the survey noted high rates of back pain in Canadian female
caregivers with a point prevalence of 25.2% compared to 18.8% in all employed females.

The situation may be worse in the US with 52% of caregivers complaining of low back pain annually and 38% of nurses suffering enough from back pain to require time off work each year [8-10]. Carren Bersch notes:

“...while healthcare workers are the backbone of healthcare, nursing remains one of its highest risk occupations.”
“...the American healthcare worker suffers a back injury every 30 minutes [11].”

The story is similar in the rest of the world too. Aggregated data on prevalence of back pain, compiled from over 80 studies, revealed an international worldwide point prevalence of approximately 17%, an annual prevalence of 40-50% and a lifetime prevalence of up to 83% [7, 12-14]. In contrast, 15 to 20% of the general population report back pain annually [7].

These incredible rates of injury occur despite the considerable effort that has gone into reducing risk of injury in caregiving. While a considerable number of changes have been implemented over the past 30-35 years, these efforts have been largely unsuccessful [15]. Work-related musculoskeletal disorders in nursing continue to rise during a period of steady decline in the rates of most other occupational injuries since 1992 [3, 16].

One reason for the increasing back injury rates may be the rise in obesity. Now that 55% of the US population is overweight or obese, some believe patient weight is a contributing factor [11]. Others believe having a larger proportion of overweight caregivers may also play a role [17]. With the direct and indirect costs of a back injury being $37,000 and $300,000 respectively, it is clear why people have been working on this problem for decades [5, 6].
Underreporting of Injuries

There is mounting evidence indicating that incidences of workplace injury are underreported [18-20]. Rates of injury may be underestimated by 30 to 70%. Kenneth Rosenman states, “[t]he current [US] national system for work-related injuries and illnesses markedly under-estimates the magnitude of these conditions” [21]. For instance, in Michigan between 61% and 68% of work-related injuries were not reported [21]. Leigh [22] insists that the US Bureau of Labor statistics missed between 33% and 69% of workplace injuries. Reported rates of back injury are flawed due to “filters” blocking the reporting of some injuries [23, 24]. For example, competition between departments may motivate keeping injuries hidden. Similarly, those without health insurance may not see a primary care physician. In such cases the injured caregiver’s choice to self-treat results in an injury that is not reported.

Trading Caregiver Health for Patient Health

An annual conference on patient handling and movement has a central theme of promoting caregiver health and well-being [25]. Every year, the conference organizers try to drive home the message that caregivers must not work to improve their patients’ health at the cost of their own. Caregivers were rated as having the most honest and ethical standards in the Gallup poll’s annual survey of professionals for the 11th year in a row in 2010 [26, 27]. Anne Hudson [28] notes:

“There is a serious disconnect between nurses being ‘the most respected profession’ and being among the most exploited, suffering preventable disabling injuries and often being fired when unable to keep lifting people”.

The exploitation of caregivers has greatly declined but there is still work needed to ensure they can do their jobs without sacrificing their health.
1.2 How the Spine Works and What Can Go Wrong

This section presents the functional anatomy of the spine followed by the most likely mechanisms of injury.

Anatomy of the Spine

The spine is made up of 33 bones (called vertebrae) in most people: 7 cervical, 12 thoracic, 5 lumbar (some have 6), 5 fused bones in the sacrum and 3 that make up the coccyx (Figure 2).

![Figure 2. Vertebral groupings of the spine](image-url)
Each vertebra is cylindrically shaped as shown in Figure 3. The exterior of the cylinder is made of stiff cortical bone, whereas the interior is cancellous (latticed/porous) bone. The top and bottom of each vertebra are called end plates and are made of deformable cartilage. Posterior to the cylindrical vertebral body are bony protrusions that form a protective channel for the spinal cord. These bony protrusions consist of transverse and spinous processes. These processes help to keep the bones of the spine aligned and also prevent the spine from twisting excessively. The posterior elements provide attachment points for both ligaments that connect bone to bone and tendons that connect muscles to bone. The muscles are what generate the forces required to support and balance the upper body and loads lifted with the hands. The muscles, ligaments and tendons also have the ability to provide proprioceptive feedback to the body.

Each vertebra is sandwiched between a pair of intervertebral discs. Like vertebrae, intervertebral discs are also cylindrically shaped. Some describe the discs as shock absorbers between the vertebrae [7]. The sides of the disc cylinder make up the *annulus fibrosus*. The annulus fibrosus is composed of collagen and Sharpey’s fibres. In the outer layers of the annulus fibrosus, the ends of these fibres attach to the vertebral body, while the inner fibres attach to the end plates on either side. In the centre of the cylinder is a gel-
like substance called the *nucleus pulposus*. Aggrecan is one of the components that make up the nucleus pulposus. Aggrecan is a negatively charged proteoglycan which makes it hydrophilic (it attracts water). Consequently, water is drawn into the nucleus pulposus creating osmotic pressure within. This pressure is constrained by a collagen fibre mesh that runs through the nucleus pulposus, the surrounding annulus fibrosus and the end plates [29]. When the spine is loaded, pressure in the nucleus pulposus increases. The nucleus pulposus in a healthy spine can sustain pressures between 0.1 MPa when lying down and up to 3MPa when lifting [30]. It is this pressurization that allows the tissue to absorb and transmit the compressive loads of the spine.

When the compressive load on the discs exceeds the interstitial osmotic pressure of the discs’ tissues, fluid is expelled out of the nucleus pulposus through the porous endplates [31, 32]. When the load is removed, water flows back in. This cyclic flow of water into and out of the disc repeats each day. The discs are loaded during the day and water is squeezed out (20% of the total intervertebral disc volume). This results in the spine shrinking lengthwise, reducing a person’s height by as much as 1.1% [7, 33]. Overnight, water re-enters the discs, increasing pressure in the disc from 0.1 to 0.24MPa [30].

Cyclic water transfer into and out of the discs is responsible for nutrient transport into the spine as well as waste transport out of the spine [34-36]. For instance, under dynamic compression, oxygen is transported into the disc while lactate is transported out of the disc [36]. The flow of nutrients and waste into and out of the nucleus pulposus is critical to the health of the disc since it is composed of living tissue, yet there is no blood supply.

**Mechanisms of Injury**

The mechanisms of back injury remain controversial. The best general treatments of this topic are by McGill [37], the U.S. Department of Labor [38], a text by Marras [7] as well as the body of work from Solomonow [39-
Taken together these four sources give us a sense of the current understanding of the causes of back injury. As Marras points out, there have historically been many researchers working within the confines of their own disciplines (biomechanics, psychophysics, genetics, etc) in isolation with the assumption that their research was mutually exclusive and exhaustive [42]. Clearly, that is too simplistic and most likely a combination of the different factors will be found to be responsible. Most recently, the porcine cervical model is being used to further probe the mechanisms of back injury [43, 44].

**Acute vs. Cumulative Injury**

In general, a back injury may be one of two types: acute or cumulative. Acute injury results when a one-time applied load exceeds the load bearing capability of tissue (ligaments, disc, vertebrae etc). For instance, if the spine is suddenly compressed, deformation of the vertebral bodies cause radial stresses in the end plates. This can result in acute injury in the form of end plate fracture (Figure 4) [37].

![Figure 4. End plate fracture](image)

Cracks in the end plates are sometimes large enough to allow liquid from the *nucleus pulposus* to pass through into the vertebral body. McGill states that “while this description of low back injury is common...experience
suggests that relatively few low back injuries occur in this manner. More commonly, injury involves cumulative trauma from repetitive sub-failure magnitude loads.” The sub-failure loads can still cause micro-fractures in the surface of the endplates when the spine is overloaded. The compressive force required for one of these micro-fractures varies from person to person (Figure 5) and depends on factors such as age, sex and cross-sectional area of the disc. The force required to damage the endplate was the basis for development of the National Institute for Occupation Safety and Health (NIOSH) limit of 3400N as the safe limit for spine compression [45].

![Graph showing compressive forces resulting in disk-vertebrae failures at L5/S1](image)

**Figure 5.** Age related decrease in vertebral compressive strength [7]

Sustaining a few micro-fractures is no cause for concern. There are no pain receptors in the endplates and so these events do not result in any pain. Most people have exceeded the spine’s load capacity at one time or another without realizing it. These fractures heal and scar over. However, individuals who are exposed to heavy lifting on a continual basis build up more and more scar tissue on their endplates. Eventually this scar tissue impedes the flow of nutrients and waste materials into and out of the disc and leads to degeneration of the discs [46]. Disc degeneration causes spinal instability and sometimes herniation, resulting in compromised nerve volume and consequently pain [7]. The flow into and out of the disc may
also be impeded by age related calcification of the articular cartilage in the vertebral end-plates [47].

One major difficulty in the prevention of back injury is that “the culminating event is falsely presumed to be the cause” of the injury, and therefore “prevention efforts are then focused on that event” [37]. Sudden severe injury often occurs because there are no pain receptors in the vertebral end plates where injury usually begins. As a result there are no warning signs as injury increases. Excruciating pain may be the first sign of extensive injury reaching nerves in the outer ring of the disc (the annulus) [38].

There is some evidence from porcine spine studies that the risk of injury to the spine is higher when it is loaded under bent or twisted postures [48-52]. This is of particular importance to caregivers as they spend large amounts of time in bent and stooped postures.

**Inflammation of Ligaments**

Some believe that occupational back pain is primarily due to inflammation driven neuro-muscular changes. In this scenario, the collagen fibres of some tissues of the spine (such as the ligaments, fascia, facet capsule etc.) exhibit micro-damage after loading [39, 40, 53, 54]. This micro-damage can result from either from static or repetitive motion of a joint and can cause the tissues to exhibit creep in length. The change in length results in a loss of stability of the spine. An inflammatory response is initiated to repair the micro-damage. Muscular hyper-excitability follows, perhaps to prevent further damage from the existing instability. For individuals with otherwise healthy spines, this may be experienced as tightness in the back muscles. But for those with underlying degeneration or compromised nerve volume, it can result in acute pain if the muscular hyper excitability results in pressure on a nerve root [39, 40, 53].
Cumulative Injury vs Genetics

The cumulative or repetitive injury model is not universally accepted [55]. A study by Videman et al. challenges this model by comparing monozygotic twins of differing body mass. They posited that if the cumulative injury model were true, there should be more disc degeneration in the heavier twin. However they found the opposite. Their alternative hypothesis is that disc degeneration is primarily determined by genetics.

The relevance of the twin study to the cumulative load hypothesis was vigorously debated in letters to the editor of the journal and remains a controversial point [56-58]. For instance, one critique pointed out that this was simply an example of adaptation of visco-elastic tissues that has been shown elsewhere [58, 59]. Another commented “emphasis on only one part of their finding leaves me baffled because of the possibility of advancing misinformation” [57].

Some believe it is a combination of genetic and metabolite related factors that results in age related deterioration of the intervertebral discs. This can cause pain in the peripheral annulus or vertebral endplate from inflammation due to contact with blood or displaced nucleus pulposus [60, 61].

Back Injury Treatments

Recurrent back injuries in caregivers are costly to the health care system and are difficult to treat successfully. They often dramatically reduce the quality of life for the injured worker in the long-term [62]. Individuals with recurrent back pain often reduce activity dramatically after a back injury because they worry about re-injury, even while they are pain-free [63].

There are a variety of treatment options for back injuries but effectiveness is limited. Nonsurgical treatments including structured exercise and/or cognitive intervention are typically attempted first. For those with chronic severe pain, surgical treatments are attempted but their efficacy remains
questionable [64]. If pain is due to spinal stenosis (a narrowing of the spinal column that puts pressure on either the spinal cord or other nerve roots) a laminectomy can be performed to create more space for the nerves. However, if the structures of the spine are unstable (if the intervertebral disc has degenerated or herniated for instance) then a fusion may be attempted. During fusion, a bone graft is placed either between the transverse processes at the back of the spine (posterolateral fusion) or in place of the disc itself once it is removed (interbody fusion) [65-67]. One study showed nearly 64% of patients remained disabled 2 years after fusion with 22% requiring follow-up operations [64]. Another study reports that eight to ten years after treatment (surgical and nonsurgical), only half of patients report improvement in pain symptoms [68, 69]. Approximately a quarter of those who were treated surgically, underwent a second surgery and had even worse outcomes than those who were treated nonsurgically or with a single surgery. One hypothesis for the ineffectiveness of surgical intervention is that fusing vertebrae together causes higher stress at the adjoining levels, possibly leading to adjacent segment disease [70, 71]. To avoid this issue, recent treatments have attempted to preserve some of the motion of the spine by using artificial disc replacements [72]. However, these treatments have yet to see widespread acceptance and the long-term outcomes remain unknown.

Therefore, we should make every effort to prevent back injury as current treatment options are limited.
1.3 Patient Lifting and Transferring

Figure 6. Floor lift

Back injuries in caregivers are often attributed to patient lifting and transfer tasks [73-77]. For instance, higher rates of back injury are seen among nurse aides, who are responsible for more patient lifting, compared to nurses [78, 79]. Similarly, injury rates among caregivers in the hospital setting tend to be lower than in the nursing home setting where there is consistently more patient lifting required [1]. Since four-fifths of nurses who provide direct care are required to lift or transfer patients in Canada [80], we will consider lifting as the obvious culprit in our investigation even though other activities may play a role as well [81, 82].

Early attempts to address the risks in patient handling focussed on body mechanics. Since awkward postures were often adopted when performing patient handling tasks, considerable work went into postural analysis of
caregiving work and training on maintaining proper body mechanics [83, 84]. However, Marras et al. soon showed that it is impossible to perform manual patient lifting activities safely whether you have one or two caregivers [85]. This explains why body mechanics training programs were largely shown to be ineffective in reducing rates of injury [13, 15, 86]. 25kg was defined as the maximum a worker should lift [45] with good body mechanics. To address caregivers and their difficulty in maintaining good body mechanics when lifting, the maximum load was reduced to 16kg [87].

![Image of ceiling lift](image)

**Figure 7. Ceiling lift**

Patient lifting is typically done with the help of mechanical lift devices in most institutions. The two most common types of mechanical lifts are floor lifts (crane-like devices on wheels shown in Figure 6) and overhead lifts (also called ceiling lifts) suspended from a track attached to the ceiling as shown in Figure 7. Mechanical lifts were introduced approximately 30 years ago in an attempt to reduce the high incidence of back injury. The use of these
devices has reduced the risk of injury to some degree [88-93]. In fact, there is considerable evidence that shows that manual lifting is never safe [85, 88, 94, 95]. Silverstein [96] goes as far as to say, “[m]echanical lifting devices are essential” and that “[e]ven with ‘good’ lifting technique, it is not possible to [safely] lift patients manually...”.

Edlich et al. describe manual lifting as a crisis and insist that no-lift policies should be put in place to reduce rates of caregiver injury [97]. No-lift policies require all patient transfers be done with mechanical lift devices. Such policies prevent injuries [5, 15, 90, 97-101] and direct economic benefits have been reported as a result of reduced compensation claims [15, 102-105].

Limitations of No-Lift Policies

Convincing policy makers to institute no-lift policies can be difficult. In Canada, only 69% of caregivers have access to mechanical lifts. Even if institutions purchase these devices, they may not be available to caregivers when they are needed. 36% of Canadian caregivers who have access to lifts, said that the equipment was not always available [80]. This is particularly true of floor lifts as the caregiver has to track down the lift before she can use it. (In contrast, overhead lifts are mounted to the ceiling, above the bed so they are always available.)

There is also the problem of caregivers choosing not to use lifts even when they are available. In many cases, there is a perception that using a lift will take longer than rounding up other caregivers to perform the lift manually [106, 107]. Time required to perform a lift is a real concern for caregivers. In a recent survey in the US, caregivers said they felt the problem of being overworked was a more pressing issue than the problem of injury rates [108]. Furthermore, a general misunderstanding of the limits of the human body leads many caregivers to believe that safe manual lifting is possible. It is commonly thought that patients can be safely manually lifted as long as proper body mechanics is used. There is positive reinforcement for this idea
because manual lifting may have been performed many times without any adverse effects \[107, 109\].

The risk associated with manual lifting increases with the weight of the patient \[110\]. With the obesity epidemic becoming cause for concern, caregivers will continue to have their limits tested during activities such as sling insertion even with so called no-lift policies in place \[111, 112\]. The process of getting a sling under a patient will certainly become an unsafe activity. Moreover, it is not simply the case that using more caregivers to perform the task will make it safer. For instance, if one caregiver can safely move 25kg, two caregivers can only move 33kg together. The mass two caregivers can lift together is only two thirds of the sum that each could lift separately. Similarly three caregivers can only lift half their combined individual lifting capacity or 38kg \[113\]. Therefore, it is impractical to safely lift a 100-150kg patient simply by increasing caregiver numbers.

The obesity epidemic is also contributing to caregivers getting heavier. This means that the spine must continuously support the increased mass of the caregiver's upper body as well as the load she lifts with her hands \[17\]. This change in the health of the work force should also be taken into consideration as we try and reduce the rates of back injury.

Some have suggested the best way to reduce injuries is to create specialized lift teams where the risk is concentrated on a few professionally trained in lifting rather than over many caregivers \[4, 114-118\]. However, we find the ethics of placing a few workers under higher risk of injury problematic.

There is some ambiguity as to what a no-lift environment is. For instance, the use of gait belts (a belt placed on the patient that has handles) is acceptable in no-lift environments. However, gait belts increase the risk of injury to a caregiver since they increase the load the caregiver is able to bear \[119\].

Even if mechanical lifts are used for all lifting and transferring activities, (moving patients from a bed to a wheelchair, from a wheelchair to a toilet
etc.) there are many other activities that increase risk of back injury \[81, 82\]. Nurses are often in bent or twisted postures such as changing bed sheets, bathing and dressing patients, wound care, etc. that may cause some of the reported injuries. There are also some activities such as repositioning patients in bed, that are viewed as much quicker to perform with a pair of nurses rather than using the available lift equipment \[17, 107\].

Finally, some activities associated with using mechanical lifts also place caregivers at increased risk of injury. In the next section I explore differences between lifts and which activities should be examined.

**Evaluations of Mechanical Lifts**

Not all mechanical lift devices reduce loads on a caregiver’s body in the same way. In one case, nurses reported higher stress ratings using floor lifts than for five manual transfer techniques \[85\]. A number of biomechanical studies have shown that the use of floor lifts results in higher loads on the caregiver than overhead lifts \[10, 89, 120-122\]. Unfortunately, these biomechanical studies had limitations of small sample size, unrepresentative subject recruitment and used a single caregiver to perform work normally performed in teams of two. These limitations have prevented these findings from making strong conclusions in favour of overhead lift use.

Zhuang et al. (1999), Keir and MacDonald (2004), Santaguida et al. (2005) and Marras et al. (2009) tested nine, seven, five and ten subjects respectively, and Rice et al. (2009) tested only one subject. Of these, only Zhuang et al. included a representative sample of caregivers with respect to age and experience. In 2004, the average age of registered nurses was 44.6 years \[80\]. In the US, the average age of nurses increased noticeably as a result of the recent economic downturn which caused many older nurses to return to work \[123\]. Some believe that the trend of retaining older nurses will continue until 2020 \[124\]. It has been shown that older workers perform tasks differently than younger workers due to changes in muscle properties \[125\]. It is particularly important to account for age based
differences since the risk of back injury increases with age [126]. Similarly, it is important to recruit trained caregivers as subjects since experience has been shown to change the way caregivers perform tasks [89]. Santaguida et al. (2005) did recruit experienced caregivers. Unfortunately, the authors recruited only young participants with an average (SD) age of 27.3 (4.2) years. Three of Keir and MacDonald’s seven subjects were experienced users of mechanical lifts though none were considered caregivers. Zhuang et al. (1999) conducted the only study to recruit older, experienced caregivers (average age 45.8 years). The remaining two studies used either novice subjects [122] or a single subject for all measurements [121].

A drawback that applies to all existing studies is that subjects operated lifts alone despite most institutions requiring two caregivers to be present when a patient is transferred. Two caregivers working together may reduce the loads experienced during the transport phase.

The forceplates used to measure ground reaction were a further drawback in Santaguida et al. and Zhuang et al.’s studies. Pilot testing indicated that the use of forceplates restricted movement and caused subjects to adopt awkward postures when operating floor lifts. Subjects were unable to get close to the floor lift and had to reach out and bend. These limitations may have led to overestimates of loading with floor lifts in previous studies.

In addition to floor lifts being harder to operate than overhead lifts, they are also harder to find on the ward when needed [80]. This is a reported barrier to their use [106].

Slings

Before a patient can actually be lifted using a mechanical lift, a sling must first be placed under him or her. The task of getting a sling under someone will be referred to as a sling insertion. Although a number of studies have evaluated mechanical lifts, there is a lack of research focused on the sling despite the potential to influence low back loads [107, 127].
Sling insertion is usually accomplished by turning or log-rolling the patient. First, the patient is rolled onto one side; the sling is aligned with the patient and partially tucked underneath. The patient is then rolled onto his or her other side to allow for the sling to be unfolded. Sling insertion has been shown to result in unsafe loads and also has the highest ratings of perceived exertion of all patient transfer tasks [10, 120, 128]. Consequently, sling insertion is found to be a barrier to lift use. Additionally, caregivers often default to manual lifting if the patient has numerous tubes and wires that get in the way of rolling the patient [106].

Existing studies of sling insertion [10, 120, 128] use methods that are problematic for similar reasons as described for mechanical lift devices. All three studies examined sling insertion as a sub-component of a larger analysis of different patient transfer methods and this limited the studies’ abilities to measure sling insertion thoroughly. Existing studies were done using only single caregivers, sample sizes were small in two studies [120, 129] and patient actors were of low body weight in two studies [10, 129]. Two of the investigations incorporated forceplates which restricted caregiver movements [10, 120]. Another limitation of all three studies was the lack of bedside reaction force measurement. Caregivers tend to obtain support by leaning against the side of the bed. Ignoring these results in substantial errors [130, 131].

There is considerable evidence that sling insertion is placing caregivers at risk of injury and therefore warrants further investigation.
1.4 Evaluating the Risk of Back Injury

We need to determine which tasks place caregivers at risk of injury so that these activities can be made safer. There are a number of ways to go about this but we have to decide on the appropriate balance of complexity and accuracy in choosing our methods [132]. As Wells et al. state, “issues of validity make instrumented measures preferable, however issues of cost and practicability tend to force investigators to less costly but less valid and less reliable measures of exposure, such as self-report questionnaires” [133]. Below, we review three types of evaluations: psychophysical, interventional and biomechanical. We determine that biomechanical evaluation strikes the right balance for our purposes.

Psychophysical Evaluation

Psychophysical assessments are based on self-reported, subjective ratings of perceived exertion and require minimal costs to execute. Typically, after performing some activity, the subject will be asked what their level of exertion was using a tool like the Borg scale [134]. This type of analysis has been used to compare different patient lifting techniques where subjects are asked to fill out questionnaires to determine a rating of perceived exertion after completing each technique [93, 135, 136].

Unfortunately, self-reported measurements are prone to error. Caregivers have a skewed view of exertion. As Holliday et al. state, “nursing staff...are self selected as nurturing by nature”. Nurses “accept pain,” “are martyrs,” or adopt a “professional attitude”. Pain is often seen to be part of the job. Some nurses have the attitude that all patients should be lifted manually (without a mechanical lift) as long as proper body mechanics are used [107]. These attitudes bias caregivers’ opinions of technologies that appear to be more time consuming. A caregiver may become frustrated by the increased set-up time required with a mechanical lift if he or she finds a two-person manual lift to be quicker. This frustration can increase the caregiver’s perceived exertion even though it is unfounded [107].
Intervention Evaluation

The most accurate way of determining the risk of injury of an activity is to look at rates of injury before and after an intervention. Metrics that can be monitored include lost workdays, workers’ compensation costs, or frequency of injury. A number of studies have taken this approach in determining the effectiveness of mechanical lift devices at reducing the risk of injury. The studies can sometimes show significant decreases in back injuries after implementation of mechanical lifts [91, 101, 102, 137]. The obvious drawback to this type of evaluation is that it requires long-term study after the intervention is in use for an extended period of time [107]. Even when such long term studies are undertaken, the variability inherent in the metrics used will limit the strength of the conclusions. For instance, a study undertaken by the Institute of Work and Health was unable to show a significant difference in injury rates as a result of an investment in lift equipment at a series of healthcare facilities in Ontario one year post intervention [138]. Typically, rates of injury must be monitored for a period of two to three years in order to find changes due to the intervention [139].

Intervention studies can be difficult to implement. For example, it would be difficult to use an intervention study to compare the effectiveness of two different types of mechanical lifts. Requiring individual nurses to use only a particular type of lift for three years would be impossible to control. Therefore, for this type of comparative study, we must settle for efficacy rather than effectiveness. All we can do is “use the currently available evidence, which is at the level of efficacy, and make recommendations about the potential for benefit...” [120].

Biomechanical Evaluation

The most common method of determining the risk of back injury is biomechanical assessment, where an activity is analyzed by considering the loads the body has to support. The term load refers to both the forces and moments the body supports. Moments are the measure of how much the
spine is being caused to bend or twist. Ideally, we are interested in determining loads on the spine (Figure 8). Loads are calculated at either the lumbosacral (L5/S1) joint (where the lumbar spine meets the sacrum as shown in Figure 9) or one joint higher at L4/L5 since these are the joints were most injuries occur [140]. For example, we can calculate external forces and moments acting at the lumbosacral joint centre. If we have an appropriate muscle model, we can convert the external moments to muscle forces to add to external forces and estimate compression or shear at the joint.

Figure 8. Forces and moments acting on the spine. a) compression; b) anterior-posterior shear; c) medial-lateral shear d) forward bending moment; e) sideways bending moment; f) twisting moment
In comparison with psychophysical evaluations, Waters states that biomechanical studies are more applicable to the prevention of musculoskeletal injuries in the caregiving field [95]. He points out that when people are asked to perform repetitive lifting tasks, the important factor to consider when deciding between biomechanical and psychophysical evaluations, is how frequently the task is done. For instance, in assembly line work where there is high repetition, workers will reach their psychophysical limit before they are at risk of damaging tissues. In such cases, surveying workers to determine the maximum acceptable weight for a given rate of repetition has been shown to limit repetitive strain injuries. In fact, this is the basis of the Snook Tables developed by Liberty Mutual that are commonly used for workplace design [141]. At high repetitions, workers tire before they are in any danger of injury. However, if loads are lifted infrequently, workers find much heavier loads acceptable to the point where the loads may exceed the body’s biomechanical limit to support those loads. This relationship between lift frequency and acceptable weight is shown in Figure 10 [95].
Figure 10. Relationship between lift frequency and load magnitude with respect to biomechanical and psychosocial limits of the human body [95]

Since caregiving requires low repetitions of heavy loads, we should focus on the biomechanical limits of the body has rather than the psychophysical ones.
1.5 Biomechanical Analysis Tools

Now that we have concluded biomechanical analyses are appropriate, this section considers how to assess whether a given activity is safe. Table 1 shows a number of options typically used to evaluate occupations that involve manual materials handling (lifting and lowering boxes for example) [142, 143] as well as to evaluate caregiver activities [136, 144-147].

### Table 1. Lifting Analysis Tools

<table>
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<tr>
<th>Tool</th>
<th>Reference</th>
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<tr>
<td>National Institute of Occupational Safety and Health lifting equation (NIOSH) [45]</td>
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<tr>
<td>Liberty Mutual “Snook” lifting tables (Snook) [141]</td>
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<tr>
<td>American Conference of Governmental Industrial Hygienists lifting threshold limit values</td>
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<tr>
<td>University of Michigan 3D Static Strength Prediction Program(3DSSPP) [148]</td>
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<tr>
<td>Washington State ergonomics rule lifting calculator</td>
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<tr>
<td>4D Watbak (Watbak) [149] [150]</td>
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<tr>
<td>3D Match [151, 152]</td>
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The NIOSH lifting equation and Snook tables define how much is safe to lift given some key activity attributes (weight of object, height of lift, number of repetitions, etc.) Other tools like Watbak and 3DSSPP are more complex and incorporate linked segment biomechanical models of the body in software. These programs can estimate internal compression and shear forces at the lumbosacral joint by combining the input force and posture data.
Input forces acting on the body can either be measured at the hands or the feet in order to determine loads at the low back. In both cases, the loading at the lumbosacral joint can be calculated as follows:

- Starting with the segments that are being acted upon distally by known external reaction forces, each segment is analyzed independently as a free body.
- The unknown joint reaction forces at the proximal end of the segment are calculated.
- The process is repeated for the next most distal segment. The proximal results of the previous segment are applied to the distal end of the next segment.
- We can end our analysis once we calculate the external forces and moments acting at the lumbosacral joint centre. These forces and moments allow us to compare one activity to another. However, if we are interested in estimating the absolute compression and shear forces acting on the lumbosacral joint, we need to know how the muscles in the trunk balance these forces and moments. For instance, often a “single equivalent muscle” model is applied. The three external moments (flexion/extension, side-bending and twisting) calculated at the lumbosacral joint can be treated as if they are balanced by a single muscle in each of the three planes allowing us to determine the internal compression and shear forces applied to the lumbosacral joint.

If internal compression and shear forces are calculated, these values can then be compared to established safe limits of $3400 \text{N}$ for compression [45] and an analogous limit for shear with proposed limits range from $500$ to $1100 \text{N}$ [7, 153-155].

If the forces are measured at the hands, a top-down process is applied. This involves calculating resultant forces starting from the subject’s hands through their arms and down their torso to his or her low back. Alternatively, if forces are measured at the feet, a bottom-up procedure is
needed. In this case, forces and moments are calculated beginning at the subject’s feet, up though his or her legs and pelvis to the low back.

Watbak is a static top-down model. To use Watbak, a mannequin is posed in the postures that are thought to result in the highest forces to the spine (Figure 11). Watbak provides an estimate of the internal compression and shear forces at the lumbosacral joint for a given posture and loading at the hands.

![Figure 11. 4D Watbak interface](image)

Unfortunately, all the tools listed in Table 1 including Watbak have three major limitations that prevent them from being used for biomechanical analyses of caregiving activities.

First, the posture of the worker cannot be precisely defined. For instance, with Watbak, a mannequin is positioned by eye rather than based on precise 3D coordinates, which can result in inaccuracies.

Secondly, it is difficult to determine loading at the hands particularly when considering activities where patient contact is involved. Loads involved in caregiving are variable and can change from one instant to the next. For example, at one point a caregiver may be supporting only a patient’s arm. In the next instant the caregiver will be supporting the arm as well as part of the trunk as the patient is rolled onto his or her side. Some have used the top-down method to find loading on the spine in caregiving tasks by estimating loads at the hands with a push-pull dynamometer during
portions of activity believed to result in the highest forces generated on the spine [135, 156, 157]. However, using force gauges likely changes the way caregivers perform some activities. For instance, caregivers often manoeuvre floor lifts by pushing them with their feet or by pulling from parts other than the handles. Even so, a number of studies employing top down biomechanical models relied on load cells mounted to the lift handles for collecting hand forces [121, 122, 158]. Such instrumentation forces study participants to use the lifts differently than caregivers may use it in the field. Both bottom-up and top-down methods give good estimates of loading at the low back though the bottom-up method was found to be marginally more accurate [159]. The bottom-up method also has the advantage that it is easier to measure forces at a subject’s feet.

Finally, these tools are designed to provide a loading estimate for one fixed posture at a time. They do not allow for processing loads resulting from a time varying set of postures. For instance, the mannequin in Watbak must be manually posed for each posture of interest. The posture(s) resulting in the highest forces may be overlooked.

Because of these limitations biomechanical assessments on caregivers are typically done using a set-up like the one shown in Figure 12. Participants stand on a pair of forceplates and perform patient care activities while their movements are tracked using a motion capture system. In most cases, the compression and shear forces at the lumbosacral joint are calculated and compared to the NIOSH limit for spinal compression of 3400N [10, 45, 110, 120, 137, 159-162].

The three dimensional coordinates of each segment in the body are calculated by a motion capture system. Usually the system is comprised of a set of video cameras that track reflective markers attached to the subject’s body (Figure 12).
Muscles Models

As discussed above, if internal compression and shear forces are needed, an appropriate muscle model must be chosen. The single-equivalent muscle model discussed above is simple to implement as each external moment about the lumbosacral joint is balanced by a single muscle. However, in reality, many different muscle groups balance a given external moment, some of which are antagonistic. Due to the simplifying assumption made in the single muscle model, results can be inaccurate. As Kingma et al. point out, single equivalent muscle models “only provide an estimate of net external loading in terms of net reactive torques and forces. Antagonistic muscle forces are not taken into account, causing considerable underestimation of spinal loading in upright posture” [163]. The authors go on to point out that a better estimate of spinal compression can be reached if antagonistic muscle forces can be estimated using electromyography (EMG) of the abdominal and back muscles as some others have done [164]. In fact, if antagonistic muscle forces are not included, one should be cautious of concluding that compression is within the safe limit. For
instance, in a study on manual lifting, Garg and Owen found that spine compression did not exceed safe limits and recommended that manual patient lifting could be considered safe as long as two caregivers were available. This conclusion was based on a static single equivalent muscle model [135]. However, a follow up study using an EMG assisted model showed spine compression of even the two caregiver activities were unsafe [85].

Similarly, recent studies have shown that an EMG assisted model is needed to accurately determine shear forces in the spine [122, 164, 165]. Based on one of these studies, floor lifts were found to be unsafe as they result in shear forces that exceed safe limits.

Unfortunately, the use of EMG adds considerable complexity to the data collection process. The time required for setup combined with invasiveness of EMG measurement make it unsuitable for use in the field [166]. It is also important to note that while the absolute loading values may be underestimated with a single-equivalent muscle model, differences in loading between two activities are still valid [167]. One available compromise for including co-contraction in field measurement without the need to measure EMG is to use McGill et al.’s (1996) polynomial for predicting compression from the three external moments estimated at the low back [168]. Unfortunately, there is no such equation for estimating shear loading. Reviews of available biomechanical assessment methods agree that there is no gold standard and that each method has its own limitations [125, 163].

**Motion Capture**

In order to perform a bottom-up inverse dynamic analysis, some method of capturing the position of the lower body is needed. Typically, this is done using an optical motion capture system. Optical systems can be difficult to use outside the laboratory environment. As Marras et al. point out, since analyses with video based motion capture systems are “limited by the field
of vision of the camera” and “jobs that require the worker to move to several work stations are extremely difficult to observe” [169]. Marras et al. go on to say that optical “motion analysis systems are often technically unable to accurately monitor a worker under typical work conditions. These systems require that joint markers be placed upon the worker that must be viewed by the video cameras at all times. In many industrial environments these markers may not be visible to the video cameras due to machinery, equipment, assembly lines, other workers, mist, poor lighting, etc”.

Another commonly used motion capture system detects a magnetic field to determine the position of markers (eg. Fastrak, Polhemus, Colchester, VT). The main drawback of these systems is that any nearby metal objects cause aberrations in the magnetic field and result in errors in position estimates.

**Alternative Methods**

The limitations of conventional motion capture systems have motivated the development of alternative methods where either traditional force or posture information is not needed. Kingma et al. have suggested two alternatives to the optical systems. The first is an electromyography-based (EMG-based) model where four pairs of EMG electrodes are attached to both sides of the midline at T10 and L3 locations [163]. Others have also used similar methods [170]. Lumbosacral extensor torque is calculated by comparing the EMG signals with static calibration values.

A second approach that Kingma et al. tested made use of the same EMG signals but also incorporated data from an accelerometer at T10 and an artificial neural network (ANN). “The net torque [at the L₅/S₁ joint] is estimated in two separate components: one being the component generated by posture and movement of the trunk plus head and the other being the component generated by arm movement plus manual load handling”. The first component is calculated using a “basic cantilever model” including linear and angular accelerations (the ANN was not used in this calculation).
The second component is estimated from the EMG signals taking the trunk angle and trunk velocity as modifiers of the relationship between EMG and net torque using the ANN.

Unfortunately, both methods suffer from large uncertainty in the estimations of net torque. The errors were $25.5 \pm 33.4\%$ and $17.3 \pm 10.5\%$ in the “EMG only” and “EMG, accelerometer and ANN” setups respectively.

Lumbar Motion Monitor

One tool that takes a different approach to determining the risk of back injury is the AcuPath Industrial Lumbar Motion Monitor (iLLM) (Chattanooga, Group, Chattanooga, USA) (Figure 13). This widely used tool [136, 169, 171-176] consists of a spinal exoskeleton equipped with relative angular position sensors that are able to monitor flexion and twisting of the spine in three dimensions. From this data, moment, frequency of lift, maximum sagittal flexion, average twisting velocity, and maximum lateral velocity are taken and fed into the Ohio State University Risk Model to determine risk of injury for a given activity [177]. In their review of this tool Marras et al. state, “[t]he LMM is an exoskeleton of the spine that is instrumented so that instantaneous changes in trunk position, velocity and acceleration can be obtained in three-dimensional space” [169].
The iLLM has been shown to provide accurate and reproducible data (both intra-subject and inter-subject reproducibility) [174] but has the drawbacks that it is expensive and requires the use of a top-down inverse dynamic analysis.

**Self-report**

One study attempted to estimate spine compression by asking participants to self-report trunk and arm postures [178]. Unfortunately, the authors found that self report was not accurate enough in determining absolute values of forces generated on the spine, though it did capture relative differences between tasks.

**Safe Limits**

We have seen that collecting accurate internal compression and shear estimates requires complex methods that are not suitable for field use. Part of the reason we are interested in accurate absolute internal values rather than the external forces and moments (that are easier to measure) is so that we can compare with established safe loading limits of 3400N NIOSH limit for compression and 500-1100N limit for shear. However, we need to evaluate the relevance of applying such limits for caregiving tasks.
For instance, Waters et al. described how they came up with the 3400N limit. The NIOSH limit was the result of data from two cadaver studies as well as psychophysical and epidemiological assessments [45]. The cadaver studies showed that the mean compressive strength of lumbar segments to be 4400N with standard deviation of 1880N [179]. Assuming a normal distribution, 30% of the vertebrae would have sustained damage even below the NIOSH limit. The second study found the compressive strength to range from 2100N to 9600N and in this case 21% of the segments fell below the 3400N limit [180].

Data from psychophysical studies were also involved in the creation of the 3400N limit. The maximum-acceptable-weight-of-lift is defined as the amount of weight a person chooses to lift under given conditions. There is strong correlation between the incidence of back injury from a task and the percentage of experienced workers who judge that task to be unacceptable. The rates of injury significantly increase for tasks acceptable to less than 75% to 90% of the workers [45, 181]. Loads generating compression of 3400N were found to be acceptable to 99% of males but only 75% of females. Waters et al. state that at this level, 90% of the population is protected assuming you have a 50/50 ratio of males to females in the workplace. However, in Canada 95% of registered nurses are female [182]. In addition, female cadaver spines were found to withstand only two-thirds the compressive load of male cadaver spines of the same age [183].

In a review of Waters et. al’s paper, Jager and Luttman state that Waters et al. used flawed logic to arrive at the NIOSH limit. Their critique concludes, “it must be summarized...that this limit is supported neither biomechanically nor epidemiologically”. Jager and Luttman go on to say, “studies on lumbar compression strength have shown that the load-bearing capacity varies over a wide range ... due to age and gender.” Jager et al. conclude all Waters et al. “prove is that the rate of low-back disorders increases with an increase in compressive force” [183].

Age is also an important factor when determining safe lifting limits. The risk of injury increases with age and this is particularly relevant for the
caregiver workforce. The average age of registered nurses in Canada is 44.6 years and approximately 68% of the nursing workforce in Canada in 2004 was over the age of forty [182]. In the US, 62% of caregivers are 50 or older [108]. This link between age and back injury may be related to the increase in spinal shrinkage with age found by Kingma et al. They found older subjects suffered from a greater loss of stature after a series of lifting trials [184]. This accelerated creep effect suggests that older caregivers are more susceptible to back injury from cumulative trauma.

We should use caution when applying limits like the NIOSH limit to caregivers who are older and predominantly female. Since we do know that a reduction in force reduces the risk of back injury [183, 185], our goal will be to identify which activities result in the highest levels of loading on the spine. With this information, we can redesign the tasks to reduce loading regardless of whether the absolute compression or shear forces are above or below given limits. If absolute compression and shear limits are no longer our objective, we can consider the use of simpler measurement techniques such as single equivalent muscle models or even avoiding the calculation of internal loads altogether. Instead, we can compare activities using external forces and moments.

Cumulative Loading

There is increasing agreement that injuries are not only the result of excessive peak loading (compression or shear) but that cumulative loading also plays a role [186-192]. Cumulative load is the calculated by taking the integral of force (the area under the force curve). Structures of the spine deform slowly and the risk of injury increases with these changes. The first evidence of the importance of cumulative load was provided by Kumar who showed a relationship between cumulative load and back pain experienced by health care aides [186]. Norman et al. presented epidemiological evidence that cumulative loading measured at the hands could be used to delineate those with and without back pain [187]. Winkel and Mathiassen agree, suggesting that evaluations should be characterized not only by the
magnitude of force but also duration and repetition [193]. Finally, in a study of sheep shearers, Gregory et al., found that while acute loads do not exceed the NIOSH limit, the cumulative loads were very high due to extreme postures that were held for extended periods of time. This was put forward as the likely explanation for the high rates of back injury in these workers [194].

Cumulative load is particularly relevant to the use of mechanical lifts. Daynard et al. found that while mechanical lift devices did reduce peak loads, in some cases cumulative load was increased [189]. The authors point out that the focus often falls on peak forces because it is a more tangible measure while the benefits of reducing cumulative loading are only seen long-term [189]. With mechanical lift devices, caregivers now perform more repetitive, sustained lifting with lighter loads and therefore cumulative loads may be rising [195].

Research into establishing a threshold limit value for cumulative spine loading has been slow to evolve [151]. Germany has been progressive in this regard and has defined a recommended dose limit of 19.8MNs per shift [196]. However, the validity of this dose limit has yet to be demonstrated [191]. The lack of focus on cumulative load limits is partially due to the difficulty of estimating cumulative load exposure using existing biomechanical methods. As mentioned previously, two sets of data are needed to calculate the load on the spine: (i) body posture data and (ii) loading data. Traditional motion capture and force plate systems require the subject to remain stationary. Perhaps this is reasonable for an assembly line worker who stands in one place, but it cannot capture a caregiver’s activities as he or she moves from room to room. Without a loading profile for the entire day, it can be difficult to draw useful conclusions. For instance, if a task is redesigned so that it can be completed faster, the cumulative load associated with that task will be reduced. However, if the caregiver performs additional tasks with this extra time, there may not be any net benefit. For this reason Fischer et al. point out that time
standardization is needed for cumulative load estimates to be useful [197] and ideally, cumulative load needs to be measured over the entire workday.

There have been a number of attempts to measure cumulative loading in the field [191]. A survey of such studies across a number of industries found that most relied on observational data to define the workers posture, using either self-report or video recording and rough estimates of external loads. Some of these studies benefit from repetitive activities done at a single workstation, but even so, a great deal of manual effort is needed to process the data. For instance, the study of sheep shearers was done using software called 3DMatch (University of Waterloo, Waterloo Ontario) [152]. Video recordings of subjects were taken in the field. Later, the video was processed by manually assessing the posture of the subject for each frame of video. The process allows the user to select postures for each segment from a gallery. However, because several manual operations are needed for each frame of video, this is a very labour intensive approach (even after the video data has been decimated to 3Hz). Posture matching was found to have an error of 12% when compared with loading from magnetic (FastTrack) motion capture system [151]. It is possible that our recent work with the Kinect™ sensor could reduce the time required for this approach as well as increase accuracy of the results [198]. The Kinect™ has the ability to record 3D representation of a scene while functioning much the same way as a video camera. Analysis of caregiving activities requires measurement over many non-repetitive activities in different locations and therefore will benefit from such a system.

There are two investigations that have attempted to reduce the manual computation required to estimate cumulative load on caregivers [81, 170]. The first used EMG of the back muscles to estimate spine compression [170]. The benefit of this method is that external loading does not have to be estimated. The other used a two dimensional inclinometer to log the trunk posture of caregivers [81, 82]. External loads lifted by the caregivers were estimated either as 0, 10, 25 or 50% of the patient’s weight depending on the task performed. Spinal loads were calculated throughout an entire
shift using a single equivalent muscle model. They found that patient lifting activities accounted for 4% of the eight hour duration of the shift and 10% of the total cumulative load experienced by nurses. The authors concluded that it was likely that activities other than patient lifting could be the cause of injury.

These conclusions raise an important question. The inclinometer study treated loading from all activities to add equally to the risk of injury. But, intuitively we expect a worker standing in a neutral posture or sitting during a break is not increasing his or her risk of injury. Therefore, we need a method that will weight work and rest activities differently. Based on the results of cadaver studies [180] Jager et al. argued that doubling force has more injurious effect than doubling exposure time, so the two factors should not be equally weighted [199]. Jager et al. suggest squaring the force values or even raising them to the fourth power to account for this discrepancy though the epidemiological relevance of these suggestions are unknown [191]. Waters et al. suggest developing a series of force multipliers that could be developed based on epidemiological evidence or in-vitro studies activity by activity [191]. However, considerable further work is needed until a consensus on appropriate methodology is reached.

Spine Shrinkage and Cumulative Loading

One possible method for assessing cumulative load, which by its nature takes into account biologically relevant loading, is the measurement of spine shrinkage. As discussed in section 1.2, during the day water is forced out of the intervertebral discs when the spine is under load and the spine shrinks in length. Water re-enters the spine at night when we lay down and the spine lengthens. Spine shrinkage has been shown to be linearly related to the quasi-static load on the spine [200]. However, McGill et al. found that the change in stature is somewhat unpredictable [201]. Even so, McGill says, “While subject variability (and perhaps biological variability) is a liability, it may be feasible to develop load time integrals for load exposure in the future, since the asset of the spinal shrinkage approach appears to be
that it is one of the few available techniques to assess cumulative loading. [I]t would appear that more quantification of the relationships that modulate spinal shrinkage are required to account for the variance in stature measurements”.

The accepted device for measuring stature, known as a stadiometer, requires reclining the subject at 75° head-up tilt to ensure he or she is relaxed (Figure 14). This stadiometer design has the ability to measure the stature of individuals to +/- 0.5mm.

Further study of spine shrinkage could help us to gain a better understanding of cumulative loading in caregiving work.

Figure 14. A stadiometer
1.6 Caregivers are Overworked

Canadian caregivers report being overworked with 38% reporting inadequate staffing and 54% saying they often arrived at work early or stayed late in order to get their work done. 62% reported working through breaks. 46% said they felt they were expected to work overtime hours. 67% often felt that they had too much work for one person. 45% said that they were not given enough time to do what was expected in their job and it should not come as a surprise that 57% said they had too much work to do everything well. In fact, one out of eight caregivers reported that their team had provided poor patient care [80]. The 2011 Health and Safety survey of 4600 caregivers in the US brought out similar concerns [108]. 74% of respondents said that being overworked was the most important health and safety concern that needed to be addressed in caregiving. Perhaps it is no surprise that many caregivers leave their jobs prematurely because of how demanding the work is, which further increases the workload of the remaining nurses [202]. The situation is not expected to get any better with staffing shortages expected to grow from 11,000 in 2007 to 60,000 in 2022 in Canada [203] and from 400,000 in 2010 to one million in 2020 in the US [204].

It is known that fatigue negatively affects physical and mental performance among caregivers leading to increased rates of medical errors [205] and facilities with higher caregiver to patient ratios report lower rates of injuries [170].

Stress vs. Strain

From a psychosocial perspective, nursing is demanding and stressful work. However, the demands and stress of a job by themselves are not associated with negative health impacts to the worker. The important factor to consider is the amount of control someone has over his or her work [206]. Our bodies maintain elevated levels of cortisol for extended periods when they are under stress and are not given the ability to resolve the issue that is
the root cause of the stress. It is the unrelenting high levels of stress that leads to strain. People in high strain jobs experience higher rates of heart disease, obesity, depression and substance abuse than counterparts in low strain work. Unfortunately, 31% of caregivers in Canada reported high job strain \([80]\). Therefore, many caregivers either do not have the tools to resolve their day-to-day challenges or they are not given the freedom to use them. Perhaps the best example of the negative impacts of strain on workers is the series of incidents beginning in 1986 where US postal workers shot and killed their managers and co-workers and gave rise to the expression *going postal* \([207]\).

On the other hand, if a worker with a stressful job is given the tools to solve problems and the autonomy to use those tools as needed, stress does not build up to into strain and cortisol levels are not sustained at elevated levels. Surgeons and professional athletes are examples of occupations where there are very high demands but the worker has a high degree of control and therefore the negative effects of strain are not seen \([206]\).

### 1.7 Summary

Back injury remains a problem among caregivers despite on-going efforts to address the issue. There are three possible reasons:

- Caregivers are not using lifts. (Either certain institutions have not implemented lifts or caregivers that have access to lifts choose not to use them.)
- The use of mechanical lifts exposes caregivers to unsafe loads. (This is complicated by the issue of both patients and caregivers getting heavier.)
- Back injuries are caused by activities other than patient lifting and transfers.

Our best option for evaluating use of mechanical lift devices is a bottom-up biomechanical analysis. We should try to recruit trained caregivers as subjects and select moderately heavy patient actors for these investigations.
Ideally we are interested in peak and cumulative loading; however tools for measuring cumulative load are limited. Although some evaluation of lift devices has already been done, there are still a number of gaps in our knowledge that prevent us from making evidence based recommendations to change institutional guidelines. Finally, we should keep in mind that caregivers are overworked and under considerable strain. Anything we can do to reduce workload would be beneficial to the caregiving community.
2 Hypotheses

In this section, we convert the three reasons for why rates of back injury in caregivers continue to rise listed in section 1.7 to testable hypotheses labelled H1 to H3. This work focuses on H2 by undertaking biomechanical evaluations of existing mechanical lift equipment as well as the design and testing of new tools to determine the best ways to reduce loading on caregivers. Previous work indicates that floor lift maneuvering and sling insertion are the activities we should focus on. Throughout our evaluations, we will keep the other two hypotheses in mind and comment on how our findings are relevant to H1 and H3.

H1: Caregivers do not always use mechanical lifts for patient lifting activities.

H2: Some patient lifting activities done using mechanical lifts result in unsafe loading on a caregiver’s spine.

H2.1.1: Floor lifts result in higher loading than overhead lifts.

H2.1.2: Two caregivers operating a floor lift result in lower loading on caregivers than a caregiver working alone.

H2.1.3: Two caregivers operating an overhead lift result in lower loading on caregivers than a caregiver working alone.

H2.2.1: More-experienced caregivers are exposed to lower loading than less-experienced caregivers when operating a floor lift.

H2.2.2: More-experienced caregivers are exposed to lower loading than less-experienced caregivers when operating an overhead lift.

H2.3.1: Sling insertion result in loading of the spine in excess of the 3400N safe limit for spine compression.
H2.3.2: Two caregivers performing sling insertion experience lower loading than a caregiver working alone.

H2.4.1: Using SlingSerter™ to perform sling insertion takes longer than using the conventional sling insertion method.

H2.4.2: SlingSerter™ has the potential to reduce loading on caregivers.

H2.5: Spine shrinkage can be used to estimate cumulative compression of the spine.

H3: Activities other than patient lifting result in loads in excess of the 3400N NIOSH limit for spine compression or the 1000N spine shear limit.

As we investigate these hypotheses, we will keep the caregiver’s work environment in mind. Our primary focus will be on caregivers in the clinical context where caregivers report being consistently overworked. We will be ready to exploit opportunities to reduce caregiver workload since we are aware of its negative effects including increased caregiver error and injury.

Our specific objectives to address H2 are listed in Chapter 4.
3 Better Tools for Biomechanics

Biomechanical evaluation appears to be the most effective method for determining the cause of back injury in caregivers. Specifically, the single-equivalent-muscle based bottom-up inverse dynamic measurement strikes a good balance between practicality and accuracy for field work. However, previous work done using this type of assessment has had three major limitations:

1) In cases where activities involved a bed, bedside reaction forces were not recorded.
2) Forceplates were used to measure ground reaction forces and moments. This limited studies to the laboratory environment and restricted participants’ movement since they had to keep their feet on the forceplates.
3) The caregiver participant had to remain within the field of view of a motion capture system. This limits measurement to activities that can be confined to this small space.

Our attempts at addressing these three limitations are discussed in sections 3.1 to 3.3.

3.1 Bedside Reaction Forces

Caregivers often lean on the patient’s bed for support while partaking in lifting activities. When measuring spinal loading using a bottom-up inverse dynamic analysis, the bedside reaction forces must be taken into account. Skotte et al. report that “...bedside reaction moment contributes significantly to the total moment and could lead to substantial overestimation of if not appropriately included in the calculations” [130]. The free body diagram in Figure 15 demonstrates why this is the case. Not measuring $F_{\text{bed}}$ means that the moment at the lumbosacral joint resulting from the horizontal component of $F_{\text{ground}}$ will no longer be cancelled by the moment resulting from $F_{\text{bed}}$. If bedside reaction forces are not recorded and
participants must be instructed to avoid contact with the bed, low back moment will again be overestimated because caregivers will have to bend and squat to maintain stability (shown in Figure 15).

![Free body diagrams of caregiver participants when allowed to lean on bedside and not.](image)

Figure 15. Free body diagrams of caregiver participants when allowed to lean on bedside and not. $F_{\text{load}}$ is the force applied by the caregivers hands, $F_{\text{bed}}$ is the bedside reaction force, $F_{\text{ground}}$ is the ground reaction force, $F_{\text{gravity}}$ represents the force of gravity acting on the caregiver and $M_{\text{L5/S1}}$ is the net moment generated at the lumbosacral joint. The moment calculated at the lumbosacral joint is overestimated if caregivers are not allowed to lean on the bed or if they lean on the bed but bedside reaction forces are not measured.

Others have shown considerable differences in muscle recruitment patterns when participants were asked to lift objects while leaning and not leaning on a 70cm tall barrier [131]. The authors found higher muscle recruitment when participants were prevented from leaning on the barrier. They suggest installing a rigid bar with force transducers at either end to measure forces normal to the plane of the bed. Such a setup would allow the caregivers to perform their tasks more naturally.

To address this need, we developed an instrumented lean-bar. The lean-bar was constructed from a length of 3.8cm diameter steel tube measuring
210cm long and mounted across a pair of AMTI MC3A-6-1000 6-axis load cells (Advanced Mechanical Technology, Inc., Watertown, Massachusetts). Signal conditioning for the force plates and load cells were provided by four AMTI MSA-6 mini strain gauge amplifiers.
3.2 Development of Portable Ground Reaction Force Measurement Systems

Portable instrumentation for biomechanical analysis was required to take measurements in a nursing ward. There are psychosocial factors that can affect the way caregivers do their jobs that cannot be reproduced in the laboratory environment. Psychosocial risk factors include [208]:

- factors associated with the job and work environment
- factors associated with the extra-work environment
- characteristics of the individual worker

These psychosocial factors can directly affect spinal loading [187, 209-211]. This is of particular concern for caregivers as they are forced to work within many constraints. In particular for caregivers, these constraints include time limitations and space restrictions due to equipment at a patient’s bedside or other equipment such as catheters and intravenous lines.

The World Health Organization and the International Classification of Function, Disability and Health (ICF) support the idea that measurements need to take place in the field. The ICF’s biopsychosocial model is shown in Figure 16. According to this model, in order to truly understand an activity, we must take into account an assortment of contextual factors both environmental and personal [212].
Portable tools for measuring ground reaction forces in the field are needed. We developed two such portable systems that did not restrict the participant’s foot movements.

**ForceShoes**

Portable force measurement devices called ForceShoes were recently developed [213]. The initial design of the ForceShoes was similar to a child’s swing set (Figure 17). Each ForceShoe consisted of a rigid external aluminum frame that contacted the ground (the frame of the swing set). The participant’s foot was suspended from this external frame by a 6-axis load cell (AMTI MC3A-6-1000) that was coupled to a rigid internal aluminum frame (the swing). The ForceShoe supported a standard running shoe 15mm above the ground.

Figure 16. The biopsychosocial model for the ICF and WHO
This setup allows the ForceShoes to collect 6-axis force/moment data while minimizing the change in height resulting from wearing them. This design allowed ground reaction force measurements to be taken in the field, but they were heavy (~6kg) and subjects were not able to move naturally. Therefore the design was improved when smaller load cells became available (Figure 18) based on an existing design [214].

The improved ForceShoes contain two 6-axis Mini45 load cells (ATI Industrial Automation), embedded within each of their soles.
This version of the ForceShoes allows participants to move far more naturally than with the previous version. The new ForceShoes weigh only 0.80 kg each (Figure 19). The load cells can be easily detached from the upper shoe portion of the devices to allowing the devices to accommodate different sizes from men’s sizes 5 to 12 by attaching the appropriate upper to the load cell base. Signals from the four load cells are amplified using a PowerDNA Cube equipped with three DNA-AI-208 8-channel strain gage input layers (which provided signal conditioning and analog to digital conversion) (United Electronic Industries, Walpole, MA). We compared the ease of movement with the amplifier both set on the floor behind the participant and worn in a waist pack weighing 0.43kg. In pilot testing we determined that participants were able to move more naturally wearing the waist pack compared to the case of trailing cables behind them.
Extended Force Platform

While studying sling insertion, we observed that build-up of static electricity on our caregiver participant was causing the amplifier/signal conditioning unit of our ForceShoes to malfunction. We determined the source of the static charge was friction between the sling and the bed sheets caused by repeated insertion and removal of the sling, which was unavoidable during this task. Therefore, we devised a secondary method for collecting ground reaction forces when sling insertion was involved.

Ground reaction forces and moments were collected using a 203cm by 53cm by 2.5cm platform mounted on top of a pair of AMTI BP2505000-2K-3847 forceplates (Watertown, MA). The force platform was constructed using seven 203cm long, 2.5cm by 7.6cm (1” by 3”) lengths of rectangular aluminum extrusion painted black and clamped together using two pipe clamps. Double sided tape was used to keep the aluminum extrusion platform from slipping on the surface of the forceplates. The extended force platform is shown in Figure 20. This system is portable yet creates a large enough
surface that it allows the caregiver to move naturally up and down the length of the bed during the sling insertion task. A similar set-up was used in a laboratory study by Skotte and Fallentin where the authors placed four force plates side by side along the length of a bed to measure patient care activities [110].

Figure 20. Extended force platform

3.3 Better Motion Capture

The final limitation to address is the restriction imposed by existing motion capture systems. With a conventional motion capture system, participants must remain within a fixed field of view of a motion capture system. This limits activities measured by focusing on those that occur only in one part of a room.

Despite having spent considerable time trying to address this issue, a robust solution has not been reached [215]. We hope our recent work with Microsoft’s Kinect™ system may offer a portable motion capture system in the future [198]. However, for this work, we will use a conventional eight-camera Vicon (Centennial, CO) motion capture system.
4 Objectives

This section lists our objectives. They fall into three groups:

To investigate caregiver biomechanics of maneuvering overhead and floor lifts.

4.1 Compare loading of one and two caregivers maneuvering overhead and floor lifts.

4.2 Compare loading of more and less experienced caregivers maneuvering overhead and floor lifts.

To investigate biomechanics of sling insertion.

4.3 Compare loading of one and two caregivers performing sling insertion.

4.4 Evaluate the usability of SlingSerter™ in the clinical environment.

To investigate a new technique for estimating cumulative load.

4.5 Determine whether measuring spinal shrinkage can be used to estimate cumulative load.

The remaining sections of this thesis describe our progress toward achieving these objectives.
5 Floor vs. Overhead Lifts

This investigation addresses our first objective of comparing the loads experienced by caregivers using floor and overhead lifts. Previous work has shown that floor lifts are harder to use compared to overhead lifts, but recommendations in favour of the better performing devices could not be made because of limitations in the existing work. For instance, all previous studies had participants operate lifts alone rather than in pairs, as is required by most institutions. Also, most studies were limited by small sample size and did not use trained caregivers as participants. Therefore, we set out to complement existing studies by testing floor and overhead lifts operated by 21 trained caregivers working alone as well as in pairs.

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A biomechanical assessment of floor and overhead lifts using one or two caregivers for patient transfers

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Abstract

This study investigated the differences in peak external hand forces and external moments generated at the L5/S1 joint of the low back due to maneuvering loaded floor-based and overhead-mounted patient lifting devices using one and two caregivers. Hand forces and external moments at the L5/S1 joint were estimated from ground reaction forces and motion capture data. Caregivers gave ratings of perceived exertion as well as their opinions regarding overhead vs. floor lifts. Use of overhead lifts resulted in significantly lower back loads than floor lifts. Two caregivers working together with a floor lift did not reduce loads on the primary caregiver compared to the single-caregiver case. In contrast, two-caregiver operation of an overhead lift did result in reduced loads compared to the single-caregiver case. Therefore, overhead lifts should be used whenever possible to reduce the risk of back injury to caregivers. The use of two caregivers does not compensate for the poorer performance of floor lifts.

Keywords

patient handling; patient lifting; safe patient handling

5.1 Introduction

Caregivers (including nurses, nursing aids, healthcare workers, etc.) sustain injuries in the workplace at alarming rates. The Bureau of Labor Statistics reports that caregivers have the highest incidence rate for nonfatal occupational injury and illness involving days away from work [216]. In particular, the prevalence of back injury is high [9, 10] and is frequently
reported as the most common type of injury by healthcare workers [216, 217]. There is growing acceptance that these injuries are largely due to patient handling tasks [74-76, 87, 218].

The use of mechanical patient lift devices (lifts) reduces the risk of caregiver injury during patient transfers [10, 90-93, 101]. No-manual-lift policies prevent injuries [15, 90, 97-100] and have direct economic benefits as a result of reduced compensation claims [15, 102, 103, 219]. However, not all mechanical lift devices reduce loads on a caregiver's body in the same way. A number of biomechanical studies have shown that the use of floor lifts results in higher loads on the caregiver than overhead lifts [10, 89, 120-122]. Unfortunately, these biomechanical studies had limitations of small sample size, unrepresentative subject recruitment as well as the use of a single caregiver to perform work normally performed in teams of two. These limitations have prevented these findings from making strong conclusions in favour of overhead lift use.

Zhuang et al. (1999), Keir and MacDonald (2004), Santaguida et al. (2005) and Marras et al. (2009) tested nine, seven, five and ten subjects respectively, and Rice et al. (2009) tested only one subject. Of these, only Zhuang et al. included a representative sample of caregivers with respect to age and experience. In 2004, the average age of registered nurses was 44.6 years [80]. In the US, the average age of nurses increased noticeably as a result of the recent economic downturn which caused many older nurses to return to work [123]. Some believe that the trend of retaining older nurses will continue until 2020 [124]. It has been shown that older workers perform tasks differently than younger workers due to declines in muscle properties [125]. These age based differences are particularly important to account for since the risk of back injury increases with age [126]. Similarly, it is important to recruit trained caregivers as subjects since experience has been shown to change the way caregivers perform tasks [89]. Santaguida et al. (2005) did recruit experienced caregivers. Unfortunately, the authors recruited only young participants with an average (SD) age of 27.3 (4.2) years. Three of Keir and MacDonald's seven subjects were experienced
users of mechanical lifts though none were considered caregivers. Zhuang et al. (1999) conducted the only study to recruit older, experienced caregivers (average age 45.8 years). The remaining two studies used either novice subjects [122] or a single subject for all measurements [121].

A drawback that applies to all existing studies is that subjects operated lifts alone despite most institutions requiring two caregivers to be present when a patient is transferred. Two caregivers working together may reduce the loads experienced during the transport phase.

The forceplates used to measure ground reaction were a further drawback in Santaguida et al. and Zhuang et al.’s studies. Pilot testing indicated that the use of forceplates restricted movement and caused subjects to adopt awkward postures when operating floor lifts. Subjects were unable to get close to the floor lift and had to reach out and bend. It is likely that these awkward postures led to overestimates of loading with floor lifts in the previous studies.

The aim of this work is to complement the body of previously published work by filling some of the gaps discussed above. The objective of this study is to compare the loads resulting from a larger sample of experienced, older caregivers working alone as well as in pairs using floor and overhead lifts so new recommendations can be confidently made. There is particular concern for caregiving performed outside institutions. In the home environment, caregivers reported considerably higher numbers of lost work days due to injuries compared to nursing home or hospital based caregivers [220]. Home care workers are generally required to perform patient lifting activities alone [221], either as a professional or informal family caregiver. These realities, combined with an expected growth in home care services of 46% from 2008 to 2018 due to trends of shorter hospital stays [222] underscore the need to both choose the best equipment and also determine whether it is necessary to recommend adding a second caregiver to reduce loads.
5.2 Methods

Previous methods for comparing floor and overhead lifts vary considerably. Reviews of available methods agree that there is no gold standard and that each method has its own limitations [125, 163].

Our protocol was adapted from Santaguida et al. (2005). Santaguida et al. estimated compression at the L5/S1 joint using a single equivalent muscle model which did not account for coactivity of antagonistic muscles. Ignoring co-contraction has been shown to underestimate compression by 45% and shear by 70% [223]. Marras et al. [122] utilized a subject specific EMG-assisted biomechanical model to estimate the compression and shear forces along the entire lumbar spine rather than focus solely on the L5/S1 joint. Their results differed from Santaguida et al. in that spine compression never reached the 3400N NIOSH limit [45] anywhere along the spine. Instead, they found anterior-posterior shear forces in excess of the 1000N limit [153] in the mid to upper levels of the lumbar spine.

An EMG-assisted model was considered for this study as it was determined that findings from a single equivalent model could be misleading. However, adapting Marras et al.’s methods for this study was ruled out because it would be too cumbersome for use in the clinical environment with nurses. The time required for setup combined with invasiveness of EMG measurement make it unsuitable for use in the field. Parkinson et al. [166] cite similar concerns in their field studies and suggest that even measuring force and traditional 3D motion capture is too cumbersome for field work and limit themselves to 2D video for their analyses. Therefore, we chose to evaluate the two lift devices by comparing external forces and moments similar to the recent study by Rice et al. This methodology will still allow us to compare the two lifts to select the best performing one. In fact, with the increasing focus on reducing cumulative loading [192], keeping compression and shear loading below a given threshold may become less important than having the ability to choose the best performing device to reduce cumulative loads. External moments were calculated at the L5/S1 joint to be
consistent with much of the previous literature; however we agree with Marras et al. that this may not be the only joint of concern.

Our study involved estimating the hand forces and external moments at the L5/S1 joint that result from moving a patient from a bed to a wheelchair and back to a bed using floor and overhead lifts in a simulated clinical environment. We improved on Santaguida et al.’s (2005) study by collecting ground reaction forces using newly developed ForceShoes rather than forceplates to allow the caregiver to move more naturally.

**Caregivers**

Twenty-one female caregivers between the ages of 19-60 with average (SD) age of 38.9 (10.8) years were recruited through advertisements at Toronto Rehabilitation Institute. Caregivers had at least one year experience in patient lift/transfer activities using mechanical lift devices and on average (SD) had 8.7 (9.5) years of experience. The average (SD) number of lifts they performed per shift (8 hours) was 8.5 (9.2). Exclusion criteria included back injury during the previous year; pregnancy; musculoskeletal or neuromuscular injury of upper limbs, lower limbs, or back within the previous 3 months; medical conditions such as mobility impairment and cardio-respiratory problems and body mass greater than 95kg. The body mass limitation was necessary in order to not overload the ForceShoes used for measurement of ground reaction forces and moments as described in section 2.4. Unfortunately this limitation prevented us from including male caregivers as participants because they were all too heavy for the ForceShoes. However, since 95% of nurses in Canada are female [80] and since women are at even greater risk of back injury than men [126, 224] our findings will be representative of the vast majority of the caregiver population. This study was approved by Toronto Rehabilitation Institute’s Research Ethics Board and all participants provided informed consent.
Setting and Equipment

All testing was done in a patient room at Toronto Rehabilitation Institute’s E.W. Bickle Centre for Complex Continuing Care where the floors were composed of vinyl flooring over concrete. The lift equipment used in this study was on loan from ArjoHuntleigh Canada Inc. (Mississauga, Ontario) and included an ArjoHuntleigh Quick Fit (TIR - L) sling (large size), floor lift (BHM Ergolift), an overhead lift (Maxi Sky 600) and a gantry system for use with the overhead lift (EasyTrack FS). A Carroll hospital bed (Carroll Hospital Group, London Ontario) was also used in this study. Figure 21 shows the floor lift and sling used in our study and Figure 22 shows the overhead lift, sling, and gantry positioned around the bed. All of this equipment was lightly used and had not experienced any significant wear. The floor lift weighed 61.2kg unloaded and had front and rear wheels measuring 7.0cm (-2”) and 9.4cm (-3”) in diameter, respectively, with all wheels composed of hard rubber. These wheel sizes were the same as Marras et al.’s (2009) small wheel configuration. The floor lift had a length and width of 118.6cm and 65.3cm respectively. The overhead lift weighed 11.5kg and measured 39.5cm, 23.5cm and 16.0cm in length width and height, respectively. A 63.0cm long two-point spreader bar was used for sling attachment with both lifts.
Figure 21: Floor lift with quick fit sling

Figure 22: Overhead lift with quick fit sling, gantry positioned around the bed
Surrogate Patient

A 90kg male surrogate patient was asked to simulate an entirely dependent patient in all trials. During testing sessions when the 90kg surrogate patient was not available, one of three lighter male surrogate patients was used after adjusting his weight with a weighted vest and leg weights. The amount of weight added to the lower leg was calculated such that the final mass of the lower leg and foot would match that of a 90kg male based on anthropometric data given by Winter [225]. The appropriate amount of weight was strapped to the surrogate patient’s lower leg at the location of the centre of mass of the segment. This ensured that during the activities of leg lowering and leg lifting, the surrogate’s segments would simulate that of a 90kg patient as closely as possible. The remaining weight discrepancy was made up by adding weight to the vest. The final mass of the surrogate patient was recorded at each session. The mean (SD) mass of the surrogate patients over the 20 sessions was 90 ± 0.5kg.

Biomechanical Measurement

Biomechanical measurements were taken to determine the hand forces and external moments on the caregiver during the lift maneuvering activity. Two pieces of information are needed to calculate these loads: 1) ground reaction forces and moments measured at the feet (force data); and, 2) three-dimensional locations of the segments of the lower body (motion capture data).

Ground Reaction Forces and Moments

Ground reaction forces and moments were collected using our recently developed ForceShoes based on an existing design [214] using four ATI Industrial Automation Mini45 load cells (Apex, NC). Any of these load cells could be loaded to a maximum of 2000N. Since all the caregiver’s mass as well as some proportion of the patient’s mass could be supported by a single load cell, we limited caregivers recruited for our study to 95kg.
(approximately 930N). This provided a reasonable safety margin to allow for possible dynamic effects. The ForceShoes were compared to AMTI BP250500-2K-3847 forceplates (Watertown, MA) and found to be in good agreement. The root mean square (RMS) errors between ForceShoe and forceplate readings were: 6.6±5.5N, 7.8±6.5N and 9.5±8.0N in the Fx, Fy, and Fz directions respectively where x is medial-lateral, y is anterior-posterior and z is in the vertical direction. Seven members of our research team were asked to perform simulated patient care activities at the bedside (sling insertion) while wearing the ForceShoes and simultaneously standing on the forceplates with one foot on each plate. Ground reaction forces were measured in the ranges of ±75N, ±90N and 0-700N in the medial-lateral, anterior-posterior and vertical directions, respectively. Both the ForceShoes and forceplates were sampled at 50Hz. An example of the ForceShoe and the corresponding force plate output is shown in Figure 23.

![Comparison of vertical ground reaction force as measured by ForceShoe and force plate](image)

Figure 23: Comparison of vertical ground reaction force as measured by ForceShoe and force plate

The sling insertion activity was broken up into 5 trials each taking approximately 5-10 seconds to complete. Errors in the position of the
centre of pressure (COP) were found to be $3.1 \pm 2.1$mm and $3.7 \pm 2.8$mm in the x and y directions. These error measurements are consistent with measurements by others using a similar design [214]. To get an estimate of the resulting errors in external moments at the L5/S1 joint, we considered the case where the COPs under both feet were a distance of the average error away from the true centre of pressure with the heaviest possible subject allowed in the study to determine how large an error we would find. Using a 1000N subject, with an error of 3.7mm in the y direction, we find the error in the resulting external moment estimate would be 3.7Nm ($0.0037m \times 1000N$). Similarly, the propagation of the 3.1mm error in the x direction would result in an error of 3.1Nm.

Signals from the ForceShoes were sampled at 50Hz. The signals were amplified (settings: 2000 gain, 5 volt excitation) via a PowerDNA Cube equipped with three DNA-AI-208 8-channel strain gage input layers (which provided signal conditioning and analog to digital conversion) (United Electronic Industries, Walpole, MA) worn in a waist pack weighing 0.43kg. A Toshiba Satellite laptop computer running LabVIEW (National Instruments Corporation, Austin, Texas) was used to capture the force signals.

**Motion Capture System**

Motion capture data were collected at 50Hz using an eight-camera Vicon motion capture system (Centennial, CO). These data were processed using Nexus 1.4.1 to output 3D coordinates of the reflective markers. The Vicon system also included a Basler video camera which was used to collect digital video of all trials.

**Procedure**

Upon arrival at the testing session, the study was explained to the caregiver and she was asked to give informed consent. The caregivers then filled out a questionnaire which asked questions regarding their background, including
how many years of experience they had in patient lifting, which type of lift they preferred (overhead or floor), and if they had ever performed a lift alone without the help of a second caregiver using either a floor or an overhead lift.

The caregiver was asked to put on the ForceShoes and a number of 1cm diameter reflective markers. Visibility of the markers on our caregivers was limited by the use of a hospital bed and mechanical lift devices as part of the experimental set up. Therefore, to avoid marker occlusion, we adapted our marker placement such that all markers were visible from behind the caregiver. Reflective marker clusters (in groups of three) were placed bilaterally on the posterior superior iliac spine, around the knee joint (two markers equidistant from the lateral femoral epicondyle; one above and one below) and a third marker on the midline of the knee joint posterior to the knee (vertically aligned with the lateral femoral epicondyle when the caregiver was standing), as well as on the T10 vertebral spinous process as shown in Figure 24. Attached to each ForceShoe were six reflective markers, with three at the proximal end of the foot and three near the distal end. The distances from markers on the ForceShoes to the calcanei, medial and lateral malleoli, as well as the first and fifth metatarsal heads were measured so that virtual markers could be placed there for analysis. Similarly, anthropometric measurements were taken so that the 3D positions of the anterior superior iliac spines, medial and lateral femoral epicondyles could be calculated. Finally, each caregiver's height, weight and age were recorded.
Figure 24: Caregiver pushing a floor lift in the ‘solo’ condition

The bed was adjusted to a comfortable working height for the caregiver. The top surface of the mattress was an average (SD) of 88 (5) cm high. A sling was placed under the surrogate patient and he was lifted just off the surface of the bed using either the overhead or floor lift. The activity of sling insertion was not measured here as it is the focus of a companion study. The caregiver was then asked to perform the following activities: 1) Lower surrogate patient’s feet and legs off bed (Legs Down); 2) Pull floor lift 30cm backward (Pull); 3) Turn lift 90° to right (Turn); 4) Push floor lift 30cm forward (Push); 5) Lift surrogate patient’s feet and legs back onto bed (Legs Up). These activities were meant to capture the loads associated with transferring a patient from a bed to a wheelchair and back to the bed. Each Legs Down activity began with the surrogate patient’s feet on the centre line of the mattress and with the patient’s bottom 2cm above the surface of the bed. Similarly, each Legs Up activity ended with the surrogate patient back over the bed in this same position. Each activity was repeated five times before moving to the next activity. Note that we were not able to measure the activity of lowering a surrogate patient into a wheelchair as we found too many markers became occluded with the lift and wheelchair present.
The activities listed above were performed in three different experimental conditions and with two different lift devices (floor and overhead lifts) while force and motion capture data were recorded. The three conditions were: single-caregiver (solo); two-caregiver-primary (primary); and two-caregiver-secondary (secondary). In the two-caregiver conditions, the caregiver who operated the controls of the lift device during the Pull, Turn and Push activities was considered to be the primary caregiver while the caregiver responsible for guiding the body of the patient was defined as the secondary. For the Legs Down and Legs Up activities, the primary caregiver guided the patient while the secondary caregiver was responsible for moving the patient’s legs. The terms ‘primary’ and ‘secondary’ did not relate in any way to the expected load on each caregiver. The other caregiver assisting each instrumented caregiver was a member of our research team with experience in lifting and moving patients and was not instrumented in any way. Figure 25 and Figure 26 show depictions of all five activities in each of three conditions with floor and overhead lifts, respectively. In addition, Table 2 defines the primary and secondary caregiver roles in the two-caregiver conditions.
Figure 25: Depictions of the five floor lift maneuvering activities performed in each of three conditions
Figure 26: Depictions of the five overhead lift maneuvering activities performed in each of three conditions
Table 2. Primary and secondary caregiver roles for two-caregiver conditions with floor and overhead lifts

<table>
<thead>
<tr>
<th>Activity</th>
<th>Primary Caregiver</th>
<th>Secondary Caregiver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Floor Lift</td>
<td>Overhead Lift</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Brace lift device</td>
<td>Guide patient’s torso</td>
</tr>
<tr>
<td>Pull</td>
<td>Pull lift device</td>
<td>Pull patient</td>
</tr>
<tr>
<td>Turn</td>
<td>Turn lift device</td>
<td>Turn patient</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Brace lift device</td>
<td>Guide patient’s torso</td>
</tr>
</tbody>
</table>
Immediately following each testing session, the instrumented caregiver was asked to fill in a questionnaire indicating how stressful she found the single-caregiver and two-caregiver lift maneuvering trials with each of the two lift styles. The Borg CR10 scale was used, where 0 = “Nothing at all” and 10 = “Extremely strong” [134, 226].

The order of floor and overhead lift trials were alternated following an initial coin toss to prevent order effects. Similarly, the order each of the three caregiver conditions was determined using a counterbalanced Latin square design.

5.3 Data Analyses

Biomechanical Measurement

Motion capture data were processed to obtain 3D coordinates defining the posture of the caregiver for the first three successful trials for each activity/condition combination. A trial was considered successful if all reflective markers remained unoccluded for the duration of the trial. 3D motion capture data were combined with ground reaction and anthropometric data in a custom biomechanical model adapted from previous studies [120, 213, 215]. Reaction forces at the hands and external moments at the L5/S1 joint were the outcome variables calculated using our biomechanical model for each activity/condition combination. The COP for each load cell was calculated with respect to the local coordinate reference frame of each load cell. These COP coordinates were then transformed into the global reference frame using the coordinates of reflective markers mounted on the ForceShoes (three markers per load cell). Similarly, the x, y and z forces from each load cell were also transformed into the global reference frame and placed at their respective COPs.

Reaction forces were estimated at the caregiver’s hands by finding the vector sum of the forces recorded at each load cell and subtracting the force
of gravity on the mass of the caregiver. Finally, the resultant hand forces were transformed into a local coordinate frame for the caregivers body defined by the vector from the right PSIS to the left PSIS, the vector from midpoint of the PSIS to the midpoint of the ASIS and the vector along the spine from the S1 vertebra to the L5 vertebra to define the medial-lateral, anterior-posterior and vertical directions respectively.

External moments at the L5/S1 joint were calculated in the global reference frame about all three axes by summing the moments resulting from ground reaction forces at each load cell located at its respective COP as well as the moments resulting from gravity acting on the waist pack, pelvis, thighs and the lower legs (The foot and shank were considered a single rigid body. The validity of this simplification is shown in Appendix C). Mass and centre of mass (COM) values from the literature were used for body segments [225, 227, 228]. In order to calculate COMs the joint centres of the ankles, knees and hips were needed. The joint centres of the ankles and knees were estimated to be the midpoints of the medial and lateral malleoli and femoral epicondyles respectively [229, 230]. The hip joint centres were predicted using the method used by Seidel et al. [231] and the L5/S1 joint was taken to be 34% of the anterior/posterior distance between the ASISs midpoint and the PSISs midpoint [232]. Finally, the external moments were transformed to the local coordinate system defined previously. A detailed description of these calculations is given in Appendix A. The peak value for each outcome variable was determined for each trial and averaged over the three trials. The six outcome variables examined in this study are summarized in Table 3.
Table 3. Methods of determining biomechanical outcome variables

<table>
<thead>
<tr>
<th>Outcome variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial-lateral hand force</td>
<td>Description</td>
</tr>
<tr>
<td>Anterior-posterior hand force</td>
<td>Peak ground reaction force</td>
</tr>
<tr>
<td>Vertical hand force</td>
<td>(Peak ground reaction force) – (caregiver’s body mass)</td>
</tr>
<tr>
<td>Forward bending moment</td>
<td>Peak external moment calculated at the L5/S1 joint using unadjusted ground reaction forces</td>
</tr>
<tr>
<td>Side bending moment</td>
<td></td>
</tr>
<tr>
<td>Twisting moment</td>
<td></td>
</tr>
</tbody>
</table>
Statistical Analysis

A repeated measures ANOVA was run with two factors (lift type and condition) with caregivers treated as random blocks for each activity and outcome variable combination. The following planned contrasts were done using $p < 0.05$ as the cut-off for statistical significance for comparing corresponding floor and overhead lift conditions:

- floor-lift, solo-condition was compared to overhead-lift, solo-condition
- floor-lift, primary-condition was compared to overhead-lift, primary-condition
- floor-lift, secondary-condition was compared to overhead-lift, secondary-condition

Further, for each lift type, the following contrasts were done using the Tukey-Kramer correction for multiple comparisons with $p < 0.05$ as the cut-off for statistical significance to compare single and two-caregiver conditions within each lift type:

- solo-condition was compared to primary-condition
- solo-condition was compared to secondary-condition
- primary-condition was compared to secondary-condition

Ratings of Perceived Exertion

Perceived exertion data from all 21 caregivers were ranked and then an ANOVA was run with two factors (lift type and condition) with caregivers treated as random blocks using a Wilcoxon type non-parametric test. The same comparisons listed above were made using cut-off of $p < 0.05$ for statistical significance.
5.4 Results

Figure 27 shows the external forward bending moments for the Legs Down activity which is representative of the results of all six outcome variables for the Legs Up and Legs Down activities. Similarly, Figure 28 shows the external anterior-posterior force for the Pull activity which is representative of the results of all six outcome variables for the Push, Pull, and Turn activities.

Table 4 and Table 5 show the mean and standard deviation of peak hand forces and moments resulting from the lift maneuvering tasks respectively.

Table 6, Table 7 and Table 8 show the statistically significant comparisons from the ANOVA. The uncertainty in the estimates of external moments (3.4Nm and 2.9Nm) calculated at the L5/S1 joint was considerably smaller than the between caregiver variability in our sample (10-30Nm). Similarly, the uncertainty of external forces (<10N) was smaller than the between caregiver variability also (10-50N).
Figure 27. External forward bending moments for the *Legs Down* activity. Error bars correspond to standard deviation.

Figure 28. External anterior-posterior force for the *Pull* activity. Error bars correspond to standard deviation.
Table 4. Mean and standard deviation of hand forces resulting from the lift maneuvering tasks

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lift Type</th>
<th>Condition</th>
<th>Anterior-Posterior Force (N)</th>
<th>Medial-Lateral Force (N)</th>
<th>Vertical Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Floor</td>
<td>Primary</td>
<td>27.5</td>
<td>18.8</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>66.8</td>
<td>30.9</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solo</td>
<td>71.9</td>
<td>27.7</td>
<td>50.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Primary</td>
<td>19.4</td>
<td>11.0</td>
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<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>61.5</td>
<td>28.6</td>
<td>48.8</td>
</tr>
<tr>
<td></td>
<td>Overhead</td>
<td>Primary</td>
<td>27.0</td>
<td>20.0</td>
<td>21.1</td>
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<tr>
<td>Pull</td>
<td>Floor</td>
<td>Primary</td>
<td>114.5</td>
<td>27.6</td>
<td>60.4</td>
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<td>31.4</td>
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<tr>
<td></td>
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<td>125.9</td>
<td>33.3</td>
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<td></td>
<td></td>
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<td>22.7</td>
<td>8.1</td>
<td>42.9</td>
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<td></td>
<td>Secondary</td>
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<tr>
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<td>Primary</td>
<td>37.8</td>
<td>23.3</td>
<td>54.5</td>
</tr>
<tr>
<td>Turn</td>
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<td>Primary</td>
<td>97.0</td>
<td>37.4</td>
<td>112.5</td>
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<td></td>
<td></td>
<td>Secondary</td>
<td>55.7</td>
<td>22.8</td>
<td>74.2</td>
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<tr>
<td></td>
<td></td>
<td>Solo</td>
<td>103.1</td>
<td>31.6</td>
<td>123.8</td>
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<tr>
<td></td>
<td></td>
<td>Primary</td>
<td>28.9</td>
<td>24.8</td>
<td>34.6</td>
</tr>
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<td></td>
<td>Secondary</td>
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<td>24.9</td>
<td>39.7</td>
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<td>Primary</td>
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<td>Push</td>
<td>Floor</td>
<td>Primary</td>
<td>89.4</td>
<td>24.2</td>
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<td>52.6</td>
<td>20.7</td>
<td>48.7</td>
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</tbody>
</table>
Table 5. Mean and standard deviation of external moments at the L5/S1 joint resulting from the lift maneuvering tasks.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lift Type</th>
<th>Condition</th>
<th>Forward Bending Moment (Nm)</th>
<th>Lateral Bending Moment (Nm)</th>
<th>Axial Twist Moment (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
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<tr>
<td>Legs Down</td>
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<td>Primary</td>
<td>22.5</td>
<td>9.6</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>44.7</td>
<td>13.4</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Solo</td>
<td>44.7</td>
<td>18.6</td>
<td>81.9</td>
</tr>
<tr>
<td></td>
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<td>Secondary</td>
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<td>19.7</td>
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<td></td>
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<tr>
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<td>Primary</td>
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<td>14.7</td>
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<td>16.3</td>
<td>88.7</td>
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<tr>
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<td>Solo</td>
<td>40.5</td>
<td>14.7</td>
<td>82.4</td>
</tr>
<tr>
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<td>Primary</td>
<td>59.8</td>
<td>27.5</td>
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<td>10.6</td>
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</tr>
<tr>
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<td>Primary</td>
<td>32.1</td>
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<tr>
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<td>Secondary</td>
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<tr>
<td></td>
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<td>32.7</td>
<td>10.6</td>
<td>52.3</td>
</tr>
<tr>
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<td>20.5</td>
<td>12.5</td>
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<tr>
<td></td>
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<td>25.3</td>
<td>14.1</td>
<td>39.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>35.3</td>
<td>9.1</td>
<td>84.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solo</td>
<td>37.5</td>
<td>14.3</td>
<td>84.7</td>
</tr>
</tbody>
</table>
Table 6. Results of comparisons of (a) mean hand forces and (b) mean external moments at the lumbosacral joint resulting from floor and overhead lift use. Table entries indicate the lift type resulting in lower loading (better performing lift) for each comparison found to be statistically significant. NS – Not significant.

(a) Forces (N)

<table>
<thead>
<tr>
<th></th>
<th>Anterior-Posterior</th>
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<td>Secondary</td>
<td>Solo</td>
</tr>
<tr>
<td>Legs Down</td>
<td>NS</td>
<td>NS</td>
<td>Overhead</td>
</tr>
<tr>
<td>Pull</td>
<td>Overhead</td>
<td>NS</td>
<td>Overhead</td>
</tr>
<tr>
<td>Turn</td>
<td>Overhead</td>
<td>Overhead</td>
<td>Overhead</td>
</tr>
<tr>
<td>Push</td>
<td>Overhead</td>
<td>NS</td>
<td>Overhead</td>
</tr>
<tr>
<td>Legs Up</td>
<td>NS</td>
<td>Overhead</td>
<td>Overhead</td>
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</table>

(b) Moments (Nm)

<table>
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<th>Axial Twist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary</td>
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<td>Solo</td>
</tr>
<tr>
<td>Legs Down</td>
<td>NS</td>
<td>Overhead</td>
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<td>Pull</td>
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<tr>
<td>Turn</td>
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<td>Overhead</td>
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<tr>
<td>Push</td>
<td>Overhead</td>
<td>Overhead</td>
<td>NS</td>
</tr>
<tr>
<td>Legs Up</td>
<td>NS</td>
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<td>Overhead</td>
</tr>
</tbody>
</table>
Table 7. Results of pair wise comparisons of (a) mean hand forces and (b) mean external moments at the lumbosacral joint for single and two-caregiver conditions during floor lift use. Table entries indicate the condition resulting in lower loading for each comparison. NS – Not significant.

(a) Forces (N)

<table>
<thead>
<tr>
<th></th>
<th>Anterior-Posterior</th>
<th>Medial-Lateral</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solo vs Pri</td>
<td>Solo vs Sec</td>
<td>Pri vs Sec</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
<tr>
<td>Pull</td>
<td>Primary</td>
<td>Secondary</td>
<td>Secondary</td>
</tr>
<tr>
<td>Push</td>
<td>Primary</td>
<td>Secondary</td>
<td>Secondary</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
</tbody>
</table>

(b) Moments (Nm)

<table>
<thead>
<tr>
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<th>Forward Bending</th>
<th>Side Bending</th>
<th>Axial Twist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solo vs Pri</td>
<td>Solo vs Sec</td>
<td>Pri vs Sec</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
<tr>
<td>Pull</td>
<td>NS</td>
<td>NS</td>
<td>Secondary</td>
</tr>
<tr>
<td>Turn</td>
<td>Primary</td>
<td>Secondary</td>
<td>NS</td>
</tr>
<tr>
<td>Push</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
</tbody>
</table>
Table 8. Results of pair wise comparisons of (a) mean hand forces and (b) mean external moments at the lumbosacral joint for single and two-caregiver conditions during *overhead lift* use. Table entries indicate the condition resulting in lower loading for each comparison. NS – Not significant.

(a) 

<table>
<thead>
<tr>
<th>Forces (N)</th>
<th>Anterior-Posterior</th>
<th>Medial-Lateral</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solo vs Pri</td>
<td>Solo vs Sec</td>
<td>Pri vs Sec</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
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<tr>
<td></td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
<tr>
<td>Turn</td>
<td>Primary</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Push</td>
<td>Primary</td>
<td>Secondary</td>
<td>NS</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
</tbody>
</table>

(b) 

<table>
<thead>
<tr>
<th>Moments (Nm)</th>
<th>Forward Bending</th>
<th>Side Bending</th>
<th>Axial Twist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solo vs Pri</td>
<td>Solo vs Sec</td>
<td>Pri vs Sec</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Turn</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Push</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Primary</td>
<td>NS</td>
<td>Primary</td>
</tr>
</tbody>
</table>
Legs Down and Legs Up Activities

The loads resulting from the Legs Down and Legs Up activities were similar for both overhead and floor lifts. Figure 27 shows the external forward bending moment resulting from the Legs Down activity was typical of these cases. We see that for the secondary condition, the load for the floor lift was slightly higher than for the overhead lift. 15 of 36 outcome/condition combinations there were statistically significant differences. The loads resulting from the floor lift were higher in 13 of these 15 cases as in Figure 27.

It was expected that loads would be similar for overhead and floor lift use since caregivers performed the same movement regardless of the type of lift used. Video footage was reviewed to determine the reason why floor lifts resulted in higher loads. The floor lift was found to obstruct the caregiver's access to the patient in some cases. In particular, the base of the floor lift forced the caregiver to stand further away from the patient resulting in caregivers having to reach out further to move the patient’s legs in either the solo or secondary conditions.

The comparison of single and two-caregiver conditions for both Legs Down and Legs Up activities was the same for all six outcome variables. The solo and secondary conditions were not significantly different from each other while the primary condition was significantly lower than the other two conditions for both floor and overhead lifts. These differences between the primary and secondary conditions as well as primary and solo conditions were expected as the primary caregiver's only responsibility for these steps was to stabilize the lift and the patient’s torso while the secondary caregiver was responsible for moving the patient’s legs.

Pull, Turn and Push Activities

In contrast to Legs Down and Legs Up activities, the Pull, Turn and Push activities showed sizable differences in loading between the floor and
overhead lift use. In particular, forces and moments associated with the primary and solo conditions with the floor lift were significantly higher than with the overhead lift in most of the solo and primary cases (16 of 18) similar to the case in Figure 28. Differences in the secondary condition were less evident with only 11 of 18 cases found to be significantly different. However, in all of these 11 cases, use of the floor lift was found to result in higher loads.

Primary and solo conditions were significantly different in five of 18 floor lift and eight of 18 overhead lift condition/outcome cases. However, reductions in loads between the solo and primary conditions in the five floor lift cases were minimal. For instance, examining the external anterior-posterior forces for the Pull activity with the floor lift, the reduction in force going from single caregiver (solo) to two caregiver (primary) was 9%. In contrast, the corresponding reduction in load with the overhead lift was 40%. In other words, overhead lifts generated lower forces in the solo case and adding a second caregiver allowed the loads to be shared among the pair more evenly than with the floor lift.

Caregiver History Questionnaire

Tallies of caregiver responses to the caregiver history questionnaire are given in Table 9.
### Table 9. Results of caregiver history questionnaire (n=21)

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>How long have you been lifting patients?</td>
<td>Mean (standard deviation): 8.7 (9.5) years</td>
</tr>
<tr>
<td>Which type of mechanical lift device do you prefer?</td>
<td>Overhead: 20</td>
</tr>
<tr>
<td></td>
<td>Floor: 1</td>
</tr>
<tr>
<td>Have you ever performed a patient lift using a mechanical lift device by</td>
<td>Yes: 12</td>
</tr>
<tr>
<td>yourself?</td>
<td>No: 9</td>
</tr>
<tr>
<td>Do you think allowing single caregivers to perform lifts with floor</td>
<td>Yes: 1</td>
</tr>
<tr>
<td>mechanical lifting devices is beneficial to caregivers and the caregiving</td>
<td>No: 20</td>
</tr>
<tr>
<td>community?</td>
<td></td>
</tr>
<tr>
<td>Do you think allowing single caregivers to perform lifts with overhead</td>
<td>Yes: 15</td>
</tr>
<tr>
<td>mechanical lifting devices is beneficial to caregivers and the caregiving</td>
<td>No: 6</td>
</tr>
<tr>
<td>community?</td>
<td></td>
</tr>
</tbody>
</table>

Caregivers overwhelmingly preferred the overhead lift. Of the 21 caregivers surveyed, only one preferred the floor lift. When asked why, the caregiver said her preference was due to the greater flexibility afforded by the floor lift since it can be used anywhere. In contrast she felt restricted by the overhead lift as it is only useful if track is installed in a given area.

Furthermore, 15 caregivers felt that it was a good idea to allow nurses to perform lifts without the help of a second caregiver if there was an overhead lift available, but only one thought solo use was a good idea if nurses were forced to use a floor lift. In fact, 12 of our 21 caregivers stated they had performed lifts alone despite the explicit requirement for two caregivers to be present when any lift equipment was used at our test site [233]. These opinions, while subjective and anecdotal, suggest that single caregiver overhead lift use is likely considered safe by many caregivers.

### Ratings of Perceived Exertion

Table 10 and Table 11 show the comparisons of perceived exertion that were found to be statistically significant. Results of the ANOVA on ratings
of perceived exertion generally agreed with the biomechanics measurements. The one exception was the secondary condition of the pull activity where there was no significant difference in perceived exertion between floor and overhead lifts while there were significant differences in three of the six condition/biomechanical outcome combinations. Likely, this was due to a combination of caregivers in the secondary condition feeling they did not take much of the load while using the floor lift and the low loads experienced in using the overhead lift.

Table 10. Results of comparisons of ratings of perceived exertion during floor and overhead lift use (p<0.05 as the cut-off for statistical significance). NS indicates comparisons found to be not statistically significant. Table entries indicate the lift type resulting in the lower perceived exertion for each comparison.

<table>
<thead>
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<th></th>
<th>Primary</th>
<th>Secondary</th>
<th>Solo</th>
</tr>
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<tbody>
<tr>
<td>Legs Down</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Pull</td>
<td>Overhead</td>
<td>NS</td>
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<tr>
<td>Turn</td>
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<tr>
<td>Push</td>
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<td>Overhead</td>
</tr>
<tr>
<td>Legs Up</td>
<td>NS</td>
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<td>NS</td>
</tr>
</tbody>
</table>
Table 11. Results of pair wise comparisons of perceived exertion for single and two-caregiver conditions during (a) floor lift and (b) overhead lift use. The cut-off for statistical significance was p<0.05 using post hoc tests with Tukey-Kramer correction for multiple comparisons. NS indicates comparisons found to be not statistically significant. Table entries indicate the condition resulting in the lower perceived exertion for each comparison.

<table>
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<td>Pri vs Sec</td>
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<tr>
<td>Legs Down</td>
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<tr>
<td>Pull</td>
<td></td>
<td>NS</td>
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<td>Secondary</td>
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<tr>
<td>Turn</td>
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<td>Secondary</td>
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<td>Push</td>
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<tr>
<td>Legs Up</td>
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<table>
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<th>Ratings of Perceived Exertion</th>
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<td>Pull</td>
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<td>Turn</td>
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<td>Push</td>
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<tr>
<td>Legs Up</td>
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<td>Primary</td>
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</table>
5.5 Discussion

Comparison with previous findings

Our results indicate that overhead lifts require lower forces to operate than floor lifts during the transport phase. These results generally agree with the five existing biomechanical studies that compared floor and overhead lifts. Of these existing studies we can compare our results directly with Rice et al. (2009) and Zhuang et al. (1999) as these studies also report external forces. Other studies reported either internal compression and/or shear values in various joints in the spine that added in muscle forces or muscle activation [89, 120, 122].

Rice et al.’s results agree well with our findings for pushing and pulling lifts when compared with the results from their patient actors in the second heaviest category with average weight of 97 ± 7kg, the closest match to our patient actor weighing 90 ± 0.5kg. When compared with findings from Zhuang et al. (1999) we find our pushing pulling and turning forces to be considerably higher. However, this is likely due to Zhuang et al.’s use of mean force values rather than peak values.

Caregivers in the Home Environment

Our findings indicate that caregivers in the home environment should be provided overhead lifts rather than floor lifts to reduce their risk of injury. In fact, the difference between overhead and floor lifts would likely be magnified in the home where carpeting and thresholds can create additional resistance to the movement of a floor lift. Overhead lifts would be advantageous in the typical case of a caregiver working alone and loads would be reduced further with a second caregiver. Adding a second caregiver with a floor lift would not reduce loads to the same extent.
Study Limitations

Results were limited to reporting external forces and moments since the methodology did not measure antagonistic muscle co-contraction and therefore we were unable to estimate internal spine compression and shear forces. These estimates would have allowed for more definitive conclusions based on absolute internal forces rather than limiting our conclusion to relative comparisons of lift type and number of caregivers.

A second limitation was that no males were included in our sample due to the body mass restriction imposed by the use of the ForceShoes. Males and females may perform manual handling tasks differently and therefore our results may not apply to male caregivers [234, 235].

Finally, recall that our study goal was to test a best case scenario with new equipment, on a level, hard floor surface with a passive patient. We likely would have found different results with older equipment that had experienced wear, with an agitated patient or on other floor surfaces (e.g. carpet). Most likely these issues would result in larger loads, and an increased difference between overhead and floor lifts. It is difficult to predict how these increased loads would be shared between two caregivers compared to a single caregiver.
5.6 Conclusions

Overhead lifts resulted in lower loads on caregivers and are predicted to reduce the risk of back injury to caregivers. Caregivers overwhelmingly preferred overhead lifts to floor lifts. In fact, the majority of caregivers said they would consider lifting a patient alone if they had access to an overhead lift but not with a floor lift. Therefore, overhead lifts should be used rather than floor lifts whenever possible. The use of two caregivers does not compensate for the poorer performance of floor lifts. The findings of our study in combination with those from Marras et al. (2009) show that it is safe to allow caregivers to perform the transport phase alone if there is an overhead lift available rather than requiring two caregivers to always be present as is currently the case. However, there may be other activities associated with lifting and transferring patients where it may be beneficial to have two caregivers present. We are currently working on a companion study that will tell us whether there are significant differences in loading between one and two caregivers during sling application. There may be other activities that should also be investigated before we can recommend allowing caregivers to perform lift and transfer activities alone, using an overhead lift.

We acknowledge that there are a minority of circumstances where overhead lifts cannot be used because tracks cannot be installed. Since overhead lifts cannot be used in all instances, there is still a need for a better floor lift which may include powered manoeuvring capabilities.

Acknowledgements

This project was funded by a research grant provided by the Workplace Safety and Insurance Board (Ontario). We also acknowledge the support of Toronto Rehabilitation Institute who receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario (MOHLTC Grant # 06036). Equipment was funded in part by Canada Foundation for Innovation (Grant #8708), Ontario
Innovation Trust, Ministry of Research and Innovation and Toronto Rehab Foundation. The first author (TD) received funding from the National Science and Engineering Research Council as well as the MITACS Accelerate internship program. The views expressed do not necessarily reflect those of these organizations.
6 The Effect of Experience in Lift Use

The motivation for evaluating the effect of caregiver experience in lift use came from observations during the data collection of one and two caregiver lift use (Chapter 5). During data collection, we noted that caregivers who were more experienced interacted with the lifts differently than those who had less experience. Since we were only part way into our data collection at the time, we decided to balance the numbers of experienced and inexperienced caregivers we recruited to allow us to compare the effect of experience on loading.

The following manuscript was submitted for publication to the International Journal of Industrial Ergonomics on July 28, 2010 and it was accepted on August 3, 2011. The manuscript was licensed for inclusion here on January 9, 2012 under licence number 2824880802926, order 60151154. The manuscript published in the International Journal of Industrial Ergonomics did not include Figure 30 which was added here for clarity along with some additional detail in the methods section.
The effects of caregiver experience on low back loads during floor and overhead lift maneuvering activities

Tilak Dutta, Pamela J. Holliday, Susan M. Gorski, Mohammad S. Baharvandy and Geoff R. Fernie

Abstract

This study investigated the effects of caregiver experience on peak external forces and moments generated at the L5/S1 joint of the low back when maneuvering loaded floor-based and overhead-mounted patient lifting devices. Twenty caregivers were divided into more-experienced and less-experienced groups based on the product of two factors: their years of lifting experience and the frequency of lifting the caregivers had done in the past. Ground reaction forces and moments as well as motion capture data were recorded while caregivers performed five different maneuvering tasks with both lifts in each of three conditions (caregiver subjects worked alone, as the primary caregiver in a pair, and as the secondary caregiver in a pair). Six outcome measures (net external forces and moments at the L5/S1 joint) were recorded. Multivariate analyses of variance of all net external forces and moments were done separately for the floor and overhead lifts. A significant effect of experience level was found for the floor lift (p=0.006) but not for the overhead lift (p=0.163). A follow-up univariate analysis of floor lift activities found significant differences between more-experienced and less-experienced caregivers for Turn, Push and Legs Up activities.

Relevance to Industry

Previous work has shown that overhead lifts reduce the loads on caregivers compared to floor lifts. The findings of this study further underscore the need to purchase overhead lifts to protect less-experienced caregivers (including informal family caregivers) who are at increased risk of back injury when maneuvering floor lifts.
Keywords

patient transfer; patient handling; patient lifting; safe patient handling

6.1 Introduction

Caregivers (including nurses, nursing aides, healthcare workers, etc.) have the highest incidence rates for nonfatal occupational injury and illness involving days away from work according to the Bureau of Labor Statistics [216]. These injuries are largely due to patient handling tasks [74-76, 87, 218]. The use of mechanical patient lift devices (lifts) can reduce the risk of caregiver injury during patient transfers [10, 90-93, 101]. However, there are important differences between the two main types of lift devices – floor lifts (devices that roll on a set of wheels on the floor) and overhead lifts (lifts that are suspended from a track attached to the ceiling). Some qualitative research has shown that overhead lifts are preferred to floor lifts based on psychophysical measurement [93, 102, 236, 237]. Unfortunately, psychophysical measurements may over-estimate the capabilities of the body's tissues particularly when dealing with infrequent heavy lifting activities as is the case with patient handling [95]. Also, thresholds of discomfort can be lower for novice workers than for experienced workers [238]. For these reasons, biomechanical studies may be better for comparing overhead and floor lifts.

The two most relevant biomechanical studies that investigated this issue both chose to use novices (individuals with little to no experience with patient lifting) as test subjects [121, 122]. Rice et al. (2009) measured horizontal hand forces generated by a single participant to maneuver lifts while varying the weight of the patient. A total of 18 surrogate patients ranging in weight from 51kg to 146kg were pushed, pulled and turned in both floor and overhead lifts. The authors found that the floor lift required significantly higher forces to maneuver. Marras et al. (2009) performed a similar comparison but using more sophisticated measurements. The authors examined the activities of maneuvering floor and overhead lifts.
using an EMG-assisted biomechanical model to estimate the compression and shear forces along the lumbar spine of 10 participants. Marras et al. found the loading due to floor lifts to be higher than the loading for overhead lift, which agrees with Rice et al.

However, these findings from novice subjects may not provide an accurate representation of loading patterns in experienced caregivers. For instance, there are two biomechanical studies that show more experienced caregivers have different muscle activation patterns than novices [89, 239]. Both studies found significant differences between experienced and inexperienced subjects. Keir and MacDonnell found mixed results in their pilot study of patient lifting activities with three experienced subjects producing lower mean erector spinae activity but higher shoulder activity than four novice subjects. Hodder et al. had similar findings in their study of 12 novice and 10 experienced nurses who were asked to perform a series of manual patient handling tasks. However there are no studies that compare the low back loading between caregivers with different levels of experience.

The question of whether low back loading changes with experience level is of particular importance because experienced caregivers tend to be older and risk of back injury increases with age [126]. This increased risk of injury may be partially offset by the effect of increased experience and this may explain why we see lower rates of injury in older workers despite their higher susceptibility [240, 241]. There are however some studies that had the opposite finding that older caregivers had higher prevalence of back injuries than younger workers [242, 243]. This latter case is more worrisome particularly in the case of inexperienced older workers in the workforce. Similarly, informal caregivers who look after family or friends at home are at particular risk as they often are both inexperienced and older. Fourteen per cent of these informal workers report being in physical discomfort or pain [244]. The case of informal caregivers is the most troubling because these workers do not have access to the tools, training or support that their paid counterparts have at hand.
The studies that do recruit trained subjects either do not report how many years of experience their caregivers had [10, 120] or report that the subjects are not considered true caregivers [89]. Santaguida et al. (2005) and Zhuang et al. (1999) did not report the experience level of the caregivers, though they did report the mean ages of their subjects which were 27.3 and 45.8 years respectively. Caregiver mean age may give us a hint of their levels of experience. Santaguida et al. compared the loads at the L5/S1 joint resulting from three types of floor lifts and two different overhead lifts and found the loads from floor lifts to be higher than from overhead lifts. Zhuang et al. (1999) estimated the hand and L5/S1 forces required to push, pull and turn floor, overhead as well as stand-up lifts. They found that the floor lifts required the most force to move followed by the stand-up lifts and overhead lifts in that order. The three experienced participants of Keir and MacDonell’s were “experienced with all transfer methods...but were not employed as health care professionals...” (p298). In their study Keir and MacDonald (2004) compared muscle activity patterns and found higher activity for floor lifts than with overhead lifts.

The motivation for this analysis came from observations during a related study on one and two caregiver lift use [245]. During data collection for this study, we noted that caregivers who had more experience moved very differently than those who had less experience. Our objective was to examine the data collected for the related lift use study to determine if there were differences in low back loading between more-experienced and less-experienced caregivers while maneuvering floor and overhead lift devices.

6.2 Methods

In our study, we estimated the net external forces and moments that result from moving a patient from a bed to a wheelchair and back to a bed using floor and overhead lifts in a simulated clinical environment. Previous biomechanical studies of lift maneuvering activities have used methods of varying complexity to estimate low back loading since there is no gold
standard [125, 163]. We based our methods on those used by Santaguida et al. (2005) because these offered a reasonable compromise between simplicity of instrumentation to allow for data collection in the clinical environment and accuracy of force measurement. Santaguida et al. collected ground reaction forces from a pair of forceplates and kinematic data from a motion capture system and calculated compression and shear at the L5/S1 joint using a single equivalent muscle model. We improved on these methods by collecting ground reaction forces using recently developed ForceShoes rather than forceplates to allow the caregiver to move more naturally. We also chose to compare loading at the low back by calculating external forces and moments rather than internal compression and shear values. We limited our comparison to external loads because of the inaccuracies with single equivalent muscle models that do not account for co-contraction of trunk muscles [223]. However, without an accurate estimate of co-contraction it is possible this investigation obscured experience related differences between our two groups.

Caregiver Participants

A total of 21 female caregivers were recruited through advertisements at Toronto Rehabilitation Institute. Caregivers had an average (SD) age of 38.9 (10.8) years with all subjects between ages of 19 and 60. Our caregivers had an average (SD) of 8.7 (9.5) years of experience in patient lift/transfer activities using mechanical lift devices with all having at least one year of such experience. The average (SD) number of lifts they performed per shift was 8.5 (9.2). These 21 caregivers were ranked according to how much experience they had with patient lifting. A caregiver’s experience level was calculated by multiplying the number of years of experience she had with the average number of patient lifts performed per shift. Based on this ranking, the 10 caregivers with the highest experience level were placed in the more-experienced category while the 10 caregivers with the lowest experience level were placed in the less-experienced category. The data from the 21st caregiver was removed from our data set because we determined she would be unrepresentative in either group with 6.5 years of experience.
Table 12 summarizes experience and average number of lifts performed per shift for our two groups of caregivers. Matlab 7.9.0 (Mathworks, Natick, MA) was used to perform t-tests to show that the masses and heights of the caregiver subjects were not significantly different between our two groups (p=0.58 and p=0.54 for mass and height, respectively). However, age was found to be significantly different between the two groups (p=0.0097).
Table 12. A comparison of more-experienced and less-experienced caregiver groups

<table>
<thead>
<tr>
<th></th>
<th>More Experienced (n=10)</th>
<th>Less Experienced (n=10)</th>
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</thead>
<tbody>
<tr>
<td>Mean number of years working as a caregiver (SD)</td>
<td>15.35 (10.2)</td>
<td>2.25 (1.06)</td>
</tr>
<tr>
<td>Mean number of patient lifts performed per shift (SD)</td>
<td>14.10 (10.8)</td>
<td>3.60 (2.12)</td>
</tr>
<tr>
<td>Mass in kg (SD)</td>
<td>64.1 (12.2)</td>
<td>61.1 (9.5)</td>
</tr>
<tr>
<td>Height in m (SD)</td>
<td>1.62 (0.07)</td>
<td>1.64 (0.06)</td>
</tr>
<tr>
<td>Age (SD)</td>
<td>45.4 (7.6)</td>
<td>33.7 (10.3)</td>
</tr>
</tbody>
</table>
Exclusion criteria included pregnancy; musculoskeletal or neuromuscular injury of upper limbs, lower limbs, or back within the previous 3 months; medical conditions such as mobility impairment and cardio-respiratory problems. The study was approved by Toronto Rehabilitation Institute’s Research Ethics Board and all participants provided informed consent.

Setting and Equipment

All testing was done in a patient room at Toronto Rehabilitation Institute’s E.W. Bickle Centre for Complex Continuing Care with lift equipment on loan from ArjoHuntleigh Canada Inc. (Mississauga, Ontario) and included an ArjoHuntleigh Quick Fit (TIR - L) sling (large size), floor lift (BHM Ergolift), an overhead lift (Maxi Sky 440) and a gantry system for use with the overhead lift (EasyTrack FS). A Carroll hospital bed (Carroll Hospital Group, London Ontario) was also used in this study.

Surrogate Patient:

A 90 ± 0.5kg male surrogate patient was asked to simulate an entirely dependent patient. A lighter surrogate patient was used after adjusting his weight with a weighted vest and leg weights during some testing sessions if the 90kg surrogate patient was not available. The appropriate amount of weight was strapped to the surrogate patient’s lower leg at the location of the centre of mass of the segment [225]. Any remaining weight discrepancy was made up by adding weight to the vest.

Biomechanical Measurement

Measurements were taken to determine the loading of the spine at the low back during the lift maneuvering activities. Two pieces of information were needed to calculate the loading at the L5/S1 joint: 1) ground reaction forces and moments measured at the feet; and, 2) three-dimensional locations of
the segments of the lower body. Ground reaction forces and moments were collected using our recently developed ForceShoes based on an existing design [214]. The ForceShoes were found to be in good agreement with AMTI BP2505000-2K-3847 forceplates (Watertown, MA). Errors between ForceShoe and forceplate readings were: 6.6±5.5N, 7.8±6.5N and 9.5±8.0N in the Fx, Fy, and Fz directions respectively where x is medial-lateral, y is anterior-posterior and z is in the vertical direction. Signals from the ForceShoes were sampled at 50Hz. The signals were amplified (settings: 2000 gain, 5 volt excitation) via a PowerDNA Cube equipped with three DNA-AI-208 8-channel strain gage input layers (which provided signal conditioning and analog to digital conversion) (United Electronic Industries, Walpole, MA) worn in a waist pack weighing 0.43kg. A Toshiba Satellite laptop computer running LabVIEW (National Instruments Corporation, Austin, Texas) was used to capture the force signals. An eight-camera Vicon motion capture system (Centennial, CO) was used to collect motion capture data at 50Hz. Digital video of all trials was also collected on the same Vicon system using a Basler video camera.

Procedure

Upon arrival at the testing session, the study was explained to the caregiver and she was asked to give informed consent. The caregivers then filled out a caregiver history questionnaire that asked questions regarding their background including their age, number of years of experience they had in patient lifting and number of lifts they typically performed in a shift.

The caregiver then put on the ForceShoes and a set of reflective marker clusters bilaterally on the posterior superior iliac spines (PSIS), around the knee joint (two markers equidistant from the lateral femoral epicondyle, one above and one below, and a third marker on the midline of the knee joint posterior to the knee, at the same height as the lateral femoral epicondyle when the subject was standing), as well as on the T10 vertebral spinous process (Figure 29). Six reflective markers were attached to each shoe with three at the ball of the foot and three near the heel. Finally, a
number of anthropometric measurements were taken so that a custom biomechanical model of each caregiver could be created.

Figure 29. Subject performing the Legs Down activity in the ‘secondary’ condition using a floor lift.

The order of lift use was pseudo randomized and the surrogate patient was suspended 2cm above the surface of the bed in one of the two lifts after the bed height was adjusted by the caregiver. The participant was then asked to perform the activities listed in Table 13 five times each. These activities were meant to simulate the activity of transferring a patient from a bed to a wheelchair and vice-versa.

Table 13. Activities that caregiver subjects were asked to perform

<table>
<thead>
<tr>
<th>Activity</th>
<th>Abbreviated name</th>
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<tbody>
<tr>
<td>1. Lower surrogate patient’s feet/legs off bed</td>
<td>Legs Down</td>
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<tr>
<td>2. Pull floor lift 30cm backward</td>
<td>Pull</td>
</tr>
<tr>
<td>3. Turn lift 90 degrees to right</td>
<td>Turn</td>
</tr>
<tr>
<td>4. Push floor lift 30cm forward</td>
<td>Push</td>
</tr>
<tr>
<td>5. Lift surrogate patient’s feet/legs back onto bed</td>
<td>Legs Up</td>
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</table>
Each activity in Table 13 was performed by caregivers working alone as well as in pairs using both floor and overhead lifts while force and motion capture data were recorded. Caregivers performed the activity twice while working with a second caregiver: once as the primary caregiver (primary) and again as the secondary caregiver (secondary) in addition to working alone (solo). The three conditions were tested in a pseudo randomized order. The two caregivers’ responsibilities during the two-caregiver conditions are shown in Table 14. A member of our research team with experience in patient lifting was the other caregiver in the two caregiver cases and did not wear ForceShoes or reflective markers.
Table 14. Primary and secondary caregiver roles for two-caregiver conditions with floor and overhead lifts

<table>
<thead>
<tr>
<th>Activity</th>
<th>Primary Caregiver</th>
<th>Secondary Caregiver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Floor Lift</td>
<td>Overhead Lift</td>
</tr>
<tr>
<td>Legs Down</td>
<td>Brace lift device</td>
<td>Guide patient's torso</td>
</tr>
<tr>
<td>Pull</td>
<td>Pull lift device</td>
<td>Pull patient</td>
</tr>
<tr>
<td>Turn</td>
<td>Turn lift device</td>
<td>Turn patient</td>
</tr>
<tr>
<td>Legs Up</td>
<td>Brace lift device</td>
<td>Guide patient's torso</td>
</tr>
</tbody>
</table>
Data Analyses

Biomechanical Measurement

3D motion capture data were processed for the first three trials of each activity/condition combination. The motion capture data were combined with ground reaction and anthropometric data in a custom biomechanical model adapted from previous studies [120, 213, 215]. The joint centres of the ankles, knees, hips and L5/S1 disc centroid were predicted using rigid body theory. The joint centres of the ankles and knees were estimated to be the midpoints of the medial and lateral malleoli and femoral epicondyles respectively [229, 230]. The hip joint centres were predicted by adapting the method used by Seidel et al. (1995). Finally, the L5/S1 joint was taken to be 34% of the anterior/posterior distance between the midpoint between the right and left anterior superior iliac spines and the midpoint between the right and left PSIS (McNeill, et al. 1980).

Table 15 lists outcome variables that were calculated for each activity/condition combination. The vertical force outcome was normalized by subtracting the subject’s body mass to reduce variability. Net external moments at the L5/S1 joint were calculated about all three axes by summing the moments resulting from ground reaction forces as well as the moments resulting from gravity acting on the waist pack, pelvis, thighs and the lower legs (the foot and shank were considered a single rigid body) using mass and centre of mass values from the literature [227].
Table 15. Methods of determining biomechanical outcome variables

<table>
<thead>
<tr>
<th>Outcome variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>Medial-lateral force</td>
<td>Peak ground reaction force</td>
</tr>
<tr>
<td>Anterior-posterior force</td>
<td>(Peak ground reaction force) – (subject’s body weight)</td>
</tr>
<tr>
<td>Normalized vertical force</td>
<td>Peak external moment calculated at the L5/S1 joint</td>
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<tr>
<td>Forward bending moment</td>
<td></td>
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<tr>
<td>Side bending moment</td>
<td></td>
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<tr>
<td>Twisting moment</td>
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</table>

Statistical Analysis

Two multivariate analyses of variance (MANOVA) were done in SAS 9.1 (Cary, NC) using the net external forces and moments at the L5/S1 joint as the response variables and including fixed factors for condition, experience and all 2 and 3 way interactions as well as a random effect for subjects. One MANOVA was done using the data from floor lift use and the second for data from overhead lift use. In each case, a test for equality of experience across all variables was done based on Wilk’s lambda using p<0.05 as the cut-off for statistical significance.

A follow-up repeated measures analysis of variance (ANOVA) was conducted for the floor lift data using condition and experience as factors in the model which also included the possible interaction between these factors. Subjects were included in the model as a random effect. A separate model was fit for each activity, for each of the six outcome variables listed in Table 15. If a significant interaction of condition and experience was found, the repeated measures ANOVA was fit for each condition to probe the relationship further. P-values obtained from the statistical analyses were treated only as guides to expose the underlying univariate effects responsible for the observed multivariate effect therefore no adjustment was made for multiplicity of testing. Activities and/or conditions for which significant differences were found are indicated in Table 16 and Table 17.
6.3 Results and Discussion

Figure 30 shows the external forward bending moment for the Turn activity using the floor lift that were representative of the other activity/outcome combinations. Table 16 shows the comparisons of external forces at the L5/S1 joint for each activity/condition/outcome combination between more-experienced and less-experienced caregivers for both floor and overhead lifts. Table 17 shows an analogous comparison of the net external moments at the L5/S1 joint. Table 18 shows a summary of the activity/condition comparison found to be statistically significant for each outcome variable.

Figure 30. External forward bending moment for the Turn activity using the floor lift. These results are representative of our other activity/outcome combinations for the floor lift.
## Table 16. Mean and standard deviation of external forces at the L5/S1 joint resulting from the lift maneuvering tasks

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<td></td>
<td></td>
<td></td>
<td>Medial-lateral Force (N)</td>
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<td>Anterior-posterior Force (N)</td>
<td></td>
<td></td>
<td>Normalized Vertical Force (N)</td>
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<td>Mean</td>
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<td>Mean</td>
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<td>F</td>
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Table 17. Mean and standard deviation of external moments at the L5/S1 joint resulting from the lift maneuvering tasks

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Note: SD = Standard Deviation; * = Significant at p < 0.05.
Table 18. Summary of the activity/condition comparison found to be statistically significant for each outcome variable

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</tr>
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<td>Secondary</td>
</tr>
<tr>
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<td>Turn</td>
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</tr>
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<td>Floor</td>
<td>Solo</td>
</tr>
<tr>
<td>Vertical Force</td>
<td>Turn</td>
<td>Floor</td>
</tr>
<tr>
<td>Turn</td>
<td>Floor</td>
<td>Solo</td>
</tr>
<tr>
<td>Push</td>
<td>Floor</td>
<td>Solo</td>
</tr>
<tr>
<td>Legs Up</td>
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<td>Secondary</td>
</tr>
<tr>
<td>Forward Bending Moment</td>
<td>Turn</td>
<td>Floor</td>
</tr>
<tr>
<td>Turn</td>
<td>Floor</td>
<td>Solo</td>
</tr>
<tr>
<td>Push</td>
<td>Floor</td>
<td>Secondary</td>
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<tr>
<td>Legs Up</td>
<td>Floor</td>
<td>Solo</td>
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<tr>
<td>Legs Up</td>
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<td>Secondary</td>
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<tr>
<td>Side Bending Moment</td>
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<td>Twisting Moment</td>
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The results of the MANOVA of the floor lift data showed a significant effect of experience level (p=0.006). However, there was no significant effect of experience level with overhead lift use (p=0.163). Still, we note a similar trend was present with the overhead lift use as more-experienced caregivers generated lower loads in 74 of the 90 activity/condition/outcome combinations tested when compared with the less-experienced caregivers.

Further probing of the floor lift data to find the underlying univariate effects showed significant differences between more-experienced and less-experienced caregivers for the Turn, Push and Legs Up activities. The peak forces and moments resulting from these activities are shown in Figure 31.
Figure 31. Peak forces and moments resulting from the Turn, Push and Legs Up activities with the floor lift.
Differences in Movement Patterns with the Floor Lift

We reviewed video footage for trials where significant differences were found between the two groups of caregivers and noticed a number of variations in technique that could explain the increased loading on less-experienced caregivers in comparison to the more-experienced group when using the floor lift.

For the Turn activity, significant differences were found with the forward bending moments (primary and solo conditions), medial-lateral forces (solo condition), anterior-posterior forces (primary and solo conditions) and normalized vertical forces (primary and solo conditions). In the primary and solo conditions, we noted the more-experienced caregivers would often push the base of the floor lift with their feet during the pushing activity while their less-experienced counterparts tended to only use their hands to turn the lift. Using the feet to turn the lift was beneficial for two reasons. First, it reduced the forces that had to be transmitted through the spine. Second, it caused the caregiver to be closer to the lift and reduced how far they had to bend to reach it.

For the Push activity, significant differences were found with forward bending moments (secondary condition) and normalized vertical forces (solo condition). We suspect the higher bending moments during the secondary condition was the result of less-experienced caregivers not moving with the lift as it was pushed forward. Video footage showed the less-experienced caregivers tended to keep their feet planted in fixed position while attempting to guide the patient. As a result, they had to reach forward and bend more than their more-experienced counterparts who tended to position themselves closer to the lift. In the solo condition, the reduced vertical forces for more-experienced caregivers may again be the result of the use of the feet for pushing the lift while their less-experienced counterparts tended to only use their hands similar to the Turn activity. The use of feet would have reduced the net external force generated at the spine.
Finally, for the Legs Up activity, significant differences were found with forward bending moments and medial-lateral forces for secondary and solo conditions for both outcomes. These findings are consistent with our observations from video footage where less-experienced caregivers supported the patient’s legs near the heels while more-experienced caregivers provided support from higher up the leg - often midway between the ankle and knee - allowing these caregivers to bend less. In one case, a more-experienced caregiver used the patient’s pant cuff to support the lower leg as the leg was raised. Additionally, caregivers in the more-experienced group tended to minimize the amount of time they supported any of the surrogate patient’s body directly. For instance, during the Legs Up activity with the floor lift, more-experienced caregivers did not start to lift the patient’s legs until they had positioned themselves and the patient as close to the bed as possible. Less-experienced caregivers would lift and support the legs through their entire movement.

**Differences in Movement Patterns with the Overhead Lift**

Some differences between the two groups of caregivers were noted with overhead lift use even though no significant effect of experience level was found. For example, during the Turn activity with the overhead lift, more-experienced caregivers typically spun the patient with a single arm motion, remaining stationary, out of the way of the rotation. In contrast, less-experienced caregivers often chose to keep facing the patient, holding the patient with both hands. This required less-experienced caregivers to adopt awkward positions to avoid the hitting the patient’s legs and feet, the lift, the other caregiver or other items in the environment, while sidestepping along a semi-circular path to obtain the same rotation.

**Study Limitations**

The findings of this study suggest that caregivers learn how to perform lift maneuvering tasks in ways that are protective of their backs over time. It is
possible that this protection of their backs occurs at a cost to exposing other parts of the body to higher loads such as the shoulder as has been found in previous work [89, 239]. This possible trade-off of injury risk should be studied further. Similarly, the influence of experience level on the co-contraction of the trunk muscles should be studied in combination with a more detailed biomechanical model.

Future Work

More study is required to determine whether different types of training can be used to boost a caregiver’s effective experience level. The efficacy of training programs remains inconclusive. While training has been shown to improve work technique [246, 247], it has also been shown to be largely ineffective in reducing back pain, back injury or other musculoskeletal symptoms [248-250]. This work on increasing an individual’s effective experience level would be particularly important for protecting informal caregivers in the home environment – often family or friends of the patient who likely have minimal experience in their caregiving roles. It may be possible to shorten the process of gaining experience for newer caregivers by developing a set of illustrations to help teach new caregivers the ‘tricks’ that can reduce loading during key actions.

6.4 Conclusions

More-experienced caregivers generated lower loads on their low-backs compared to less-experienced caregivers when maneuvering floor lifts but not with overhead lifts. These differences appear to be due to variations in technique that allow more-experienced caregivers to limit the amount they bend as well as reduce the forces they apply using their hands by preferentially using their feet when possible to maneuver floor lifts. These findings indicate that workplaces should consider instituting greater protection for less-experienced caregivers if they are required to work with floor lifts and preferentially install overhead lifts whenever possible.
Acknowledgements

This project was funded by a research grant provided by the Workplace Safety and Insurance Board (Ontario). We also acknowledge the support of Toronto Rehabilitation Institute who receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario (MOHLTC Grant # 06036). Equipment was funded in part by Canada Foundation for Innovation (Grant #8708), Ontario Innovation Trust, Ministry of Research and Innovation and Toronto Rehab Foundation. The first author (TD) received funding from the National Science and Engineering Research Council as well as the MITACS Accelerate internship program. The views expressed do not necessarily reflect those of these organizations.
7 Sling Insertion

The studies presented in sections 5 and 6 showed that risk of injury is decreased by using overhead lifts rather than floor lifts. However, regardless of which type of lift is available, caregivers still have to struggle to get a sling under the patient before the lift can be used. The work presented in this section evaluates the activity of sling insertion to determine if it can be performed safely with one and/or two caregivers.

Recall that we experienced a malfunction in our ForceShoe system due to the build-up of static electricity during sling insertion (section 3.2). Therefore, we elected to use our extended force platform to collect ground reaction forces in this study.

For this study, we decided to estimate internal compression at the lumbosacral joint. Recall in our two previous studies, we argued that calculating internal forces could be misleading for lift maneuvering activities, since shear loading is the critical parameter. We are unable to accurately estimate internal shear values without very complex EMG assisted models. However, this study investigates sling insertion, a process that requires more bending and lifting rather than pushing or pulling. Therefore, we felt calculating internal compression was appropriate and it would allow us to compare our results with previous work using similar models. External loading will also be calculated to ensure it agrees with our findings based on internal compression.

The following manuscript was submitted for publication to Applied Ergonomics on November 1, 2011.
A Biomechanical Assessment of Sling Insertion Using One or Two Caregivers

Tilak Dutta, Pamela Jean Holliday, Susan Margaret Gorski and Geoff Roy Fernie

Abstract

This study investigates the differences in peak compression forces generated at the low back during the insertion of a lifting sling under a patient. We observed sling insertion by one caregiver working alone and two caregivers working collaboratively. Ground and bedside reaction forces, moments and 3D motion capture data were recorded while a caregiver inserted a sling under a 93kg male patient actor. We calculated the compression at the lumbosacral joint for 15 caregiver participants. External moments at the L5/S1 joint and hand reaction forces were also examined. The peak compressive loads on a single caregiver were not significantly higher than the loads on either of the two caregivers working as a pair. In fact, loads on one of the caregivers working as a two-caregiver team were higher than the load on the single caregiver for some activities. Therefore, a single caregiver performing sling insertion under a 93kg patient is at no higher risk of injury than two caregivers working together.

Keywords

patient sling; patient lifting; safe patient handling

7.1 Introduction

Caregivers (including nurses, nursing aides, healthcare workers, etc.) are consistently among the groups in the US reporting the highest rates of injury in the workplace, with the majority of these incidents being back injuries [216, 251]. Trends are the same elsewhere with prevalence of back pain among caregivers ranging from 45 to 75 percent worldwide [252]. There
is a growing consensus that these injuries are largely due to patient handling [74, 75, 87, 218] and the only way to prevent them is with the use of mechanical lift devices [90, 91, 101, 111, 219].

A number of studies have evaluated the biomechanics of mechanical lift use comparing the two most common types of lifts available: floor lifts and overhead lifts [10, 89, 120-122, 253, 254]. However, before any mechanical lift can be used, a sling must be placed under the patient. There has been very little study into the activity of inserting a sling under the patient.

Sling insertion is usually accomplished by turning or log-rolling the patient. First, the patient is rolled onto one side; the sling is aligned with the patient and partially tucked underneath. The patient is then rolled onto his or her other side to allow for the sling to be unfolded. Sling insertion is considered a demanding task that increases the risk of low back injury in caregivers [127]. There have been some attempts to quantifying the forces generated during sling application [10, 129, 137]. All three of these studies examined sling insertion as one sub-component of a larger analysis of different patient transfer methods and it would appear that this may have limited the studies’ abilities to measure sling insertion thoroughly. For instance, Silvia et al. state they chose a relatively small patient actor to reduce the risk of injury to their caregiver subjects during parts of the study that involved manual lifting. Similarly, Zhuang et al. used two female patient actors weighing 58.2kg and 77.3kg. Only Santaguida et al. used a larger patient weighing 89kg. These previous studies tended to be limited in terms of sample size also. Santaguida et al. and Silvia et al. had 5 and 6 subjects, respectively and Zhuang et al. had a larger sample of 11. Both Zhuang et al. and Santaguida et al. measured ground reaction forces using a pair of forceplates. It was unclear how, or if, reaction forces were measured by Silvia et al. Our pilot studies indicated that instructing caregivers to keep their feet within the surface of the force plates restricted movement during sling insertion. Another limitation of all three studies was the lack of bedside reaction force measurement because caregivers tend to obtain support by leaning against the side of the bed. Ignoring these forces has been shown to result
in substantial errors [130, 131]. Skotte suggests a solution by installing a rigid bar with force transducers at either end to measure forces normal to the plane of the bed. Such a set-up would allow the caregivers to perform their tasks more naturally. Finally, in all three studies the caregiver was asked to perform the sling insertion activity alone despite the fact that two caregivers would typically be required to work together in the clinical environment [255].

We are particularly interested in differences in loading between one and two-caregiver lifting activities. One of our companion studies showed that loads on a caregiver using an overhead lift device while working alone are not significantly higher than the loads generated when two caregivers work together [254]. Determining the extent to which a lifting task can be done with one caregiver and updating institutional guidelines could help address staffing shortages that are projected to get worse over the next decade.

The aim of this work is to perform a biomechanical analysis of sling insertion while addressing the limitations of previously published work, discussed above. The objective of the present investigation is to compare the compression at the lumbosacral joint in caregivers working alone and in pairs during a sling insertion activity.
There are a number of possible methods available for measuring low back loading, each with its own benefits and limitations, and therefore none is considered the gold standard \[163\]. Our protocol was adapted from Santaguida et al. (2005) who estimated compression at the lumbosacral joint using a single equivalent muscle model that did not account for coactivity of antagonistic muscles. We recognize that not accounting for co-contraction can underestimate compression by as much as 45\% \[223\]. An alternative would be to use an EMG-assisted biomechanical model similar to that used by Marras et al. \[122\] to estimate compression forces. However, such a method was ruled out for this study because EMG measurement was found to be too awkward to implement in the clinical environment because of the longer setup time and increased invasiveness. Some field-based researchers go further and consider even force measurement and 3D motion capture too cumbersome for field work and typically limit themselves to only collecting 2D video \[166\].

Therefore, we chose to evaluate the sling insertion activity by adapting Santaguida et al.’s methods and improving them in two aspects:

i) Ground reaction forces were collected using a 203cm by 53cm force platform rather than restricting caregivers to the surface of typical smaller forceplates to allow the caregiver to move more naturally.

ii) Bedside reaction forces were measured by constructing an instrumented lean-bar at the side of the bed.

3D motion capture data was also recorded. These three sets of data (ground reactions, bedside reactions and 3D motion) were then fed into a single equivalent muscle model of the spine to estimate the compression at the lumbosacral joint of the spine. We recognize absolute compression values may have been underestimated; however, this methodology allowed us to compare the relative magnitudes of the loads resulting from caregivers working alone and in pairs. Using Santaguida et al.’s model also allows us to
compare our results with the previous work. Hand forces and external moments at the lumbosacral joint were also estimated and plotted to help understand differences between the single-caregiver and two-caregiver conditions.

Caregivers

15 female caregivers between the ages of 27 and 56 with average (SD) age of 45.1 (9.3) years were recruited through advertisements at Toronto Rehabilitation Institute. Caregivers had at least three years of experience in patient lift/transfer activities using mechanical lift devices and on average (SD) had 13.0 (9.3) years of experience. The average (SD) number of lifts they performed per 8 hour shift was 6.8 (3.1). Exclusion criteria included back injury during the previous year; pregnancy; musculoskeletal or neuromuscular injury of upper limbs, lower limbs, or back within the previous three months; medical conditions such as mobility impairment and cardio-respiratory problems. Despite not including any male caregivers due to the predominance of female caregivers at our facility, we feel our sample is representative of the caregiving community since 95% of nurses in Canada are female [80]. Furthermore since women are at greater risk of back injury than men [126, 224] our findings will reflect the most vulnerable proportion of the caregiver population. This study was approved by Toronto Rehabilitation Institute’s Research Ethics Board and all participants provided informed consent.

7.3 Setting and Equipment

All testing was done in a patient room at Toronto Rehabilitation Institute’s E.W. Bickle Centre for Complex Continuing Care with lift equipment on loan from ArjoHuntleigh Canada Inc. (Mississauga, Ontario) including an ArjoHuntleigh Quick Fit (TIR - L) sling (large size), an overhead lift (Maxi Sky 440) and a gantry system for use with the overhead lift (EasyTrack FS).
A hospital bed (Carroll Hospital Group, London Ontario) was also used in this study.

**Patient Actor**

The same patient actor, a 93kg male, was used for all experiments. He was instructed to remain entirely passive for the duration of each trial and to not assist the caregiver in any way. The patient actor was placed in a supine position at the beginning of each trial with his legs straight and feet together.

**Biomechanical Measurement**

Motion capture data were collected at 100Hz using an eight-camera Vicon motion capture system (Centennial, CO). These data were processed using Nexus 1.4.1 to output 3D coordinates of the reflective markers. The Vicon system also included a Basler video camera that was used to collect digital video of all trials.

Ground reaction forces and moments were collected using a 203cm by 53cm by 2.5cm platform mounted on top of a pair of AMTI BP2505000-2K-3847 forceplates (Watertown, MA). The force platform was constructed using seven 203cm long, 2.5cm by 7.6cm (1” by 3”) lengths of rectangular aluminum extrusion painted black and clamped together using two pipe clamps. Double sided tape was used to keep the aluminum extrusion platform from slipping on the surface of the forceplates. Similarly, bedside reaction forces were recorded using a lean-bar constructed from a length of 3.8cm diameter steel tube measuring 210cm long mounted across a pair of AMTI MC3A-6-1000 6-axis load cells. Signal conditioning for the force plates and load cells were provided by four AMTI MSA-6 mini strain gauge amplifiers and collected on the Vicon A/D card at 100Hz using Nexus 1.4.1. Reflective markers were placed on the lean bar load cells as well as the force plates. The lean-bar and force platform are shown in Figure 32.
Figure 32. The setup for our study with force platform and lean-bar positioned around the bed.

Procedure

Upon arrival at the testing session, the study was explained to the caregiver and she was asked to give informed consent. The caregiver then filled out a questionnaire which asked questions about her background, including how many years experience she had in patient lifting. Next, 1cm diameter reflective marker clusters (in groups of three) were placed on the caregiver bilaterally on the posterior superior iliac spine, around the knee joint (two markers equidistant from the lateral femoral epicondyle; one above and one below) and a third marker on the midline of the knee joint posterior to the knee (vertically aligned with the lateral femoral epicondyle when the caregiver was standing), as well as on the T10 vertebral spinous process. Also markers were applied to the fifth metatarsal heads, calcanei, and lateral malleoli, and distances to the first metatarsal heads were measured so a virtual marker could be located there for analysis. Visibility of the markers on our caregivers was limited by the use of a hospital bed as part of the experimental set up. To avoid marker occlusion, we adapted our marker placement such that all markers were visible from behind the caregiver or from cameras mounted under the bed. Similarly, anthropometric measurements were taken so that the 3D positions of the anterior superior iliac spines, medial and lateral femoral epicondyles could be calculated. Finally, each caregiver’s height, weight and age were recorded. The bed height was adjusted such that the surface of the mattress was 10cm below the subject’s anterior superior iliac spine landmark.
The patient actor was asked to lie supine in the centre of the bed. Caregivers were asked to place a sling under the patient actor using the following eight steps:

1. Roll the patient onto his right side (Roll Right)
2. Align and tuck the sling partially under the patient (Tuck Sling)
3. Roll the patient back to supine (Roll Back)
4. Roll the patient onto his left side (Roll Left)
5. Unfold the sling (Sling Unfold)
6. Roll the patient back to supine (Roll Back II)
7. Adjust leg straps between the patient’s legs (Leg Straps)
8. Connect the sling straps to the overhead lift (Connect Straps)

Caregivers were asked to perform each of the eight activities above in three different experimental conditions while force, moment and motion capture data were recorded. The three conditions were: single-caregiver (Solo); two-caregiver-primary (Primary); and two-caregiver-secondary (Secondary). In the Solo and Primary conditions, the instrumented caregiver performed the sling insertion while standing on the patient’s left side. The instrumented caregiver stood on the patient’s right side during the Secondary condition. In the two-caregiver conditions, a female member of our research team with experience in lifting patients played the role of the other caregiver. Her height and weight were 169cm and 71.2kg. This caregiver was given the option of standing on a wooden platform that was the same height as the force platform (17.7cm) but elected to stand directly on the ground and no force or motion capture data were collected for her. Figure 33 shows depictions of all eight phases of the sling insertion activity in each of three conditions tested and Table 19 defines the primary and secondary caregiver roles in the two-caregiver conditions. The order the three conditions were measured was determined using a counterbalanced Latin square design.
Caregivers were given a ten-minute break when switching from one condition to the next. Switching between Primary and Secondary two-caregiver conditions, the patient actor was rotated on the bed to simulate the nurse moving to the opposite side of the bed. This let us keep our force platform and motion capture system on the same side of the bed. Before beginning, subjects practiced all eight phases of the sling insertion activity twice to familiarize themselves with the particular sling and overhead lift used in this study. Each phase was repeated five times before moving to the next phase.
Figure 33. The sling insertion task was broken down into eight phases as shown for all three experimental conditions: Solo (single caregiver), Primary and Secondary (two-caregiver). IC indicates the instrumented caregiver. The other caregiver shown above in the two-caregiver conditions was a member of our research team.
Table 19. Left and Right caregiver roles in the two-caregiver conditions for the eight phases of sling insertion

<table>
<thead>
<tr>
<th>Phase</th>
<th>Primary Caregiver</th>
<th>Secondary Caregiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll Right</td>
<td>Together, both caregivers roll the patient actor onto his right side.</td>
<td>Support patient actor balancing him on his right side.</td>
</tr>
<tr>
<td>Sling Tuck</td>
<td>Fold, align sling and tuck it partially under patient actor.</td>
<td>Support patient actor balancing him on his right side.</td>
</tr>
<tr>
<td>Roll Back</td>
<td>Together, both caregivers roll the patient actor back to supine.</td>
<td></td>
</tr>
<tr>
<td>Roll Left</td>
<td>Together, both caregivers roll the patient actor onto his left side.</td>
<td></td>
</tr>
<tr>
<td>Sling Unfold</td>
<td>Support patient actor balancing him on his left side.</td>
<td>Unfold sling fully.</td>
</tr>
<tr>
<td>Roll Back II</td>
<td>Together, both caregivers roll the patient actor back to supine once more.</td>
<td></td>
</tr>
<tr>
<td>Leg Straps</td>
<td>Lift patient’s left leg slightly and slide leg strap up between legs.</td>
<td>Lift patient actor’s right leg slightly and slide leg strap up between legs.</td>
</tr>
<tr>
<td>Connect Straps</td>
<td>Connect the three sling straps on the patient’s left side to the overhead lift.</td>
<td>Connect the three sling straps on the patient’s right side to the overhead lift.</td>
</tr>
</tbody>
</table>

Data Analyses

Motion capture data were processed to obtain 3D coordinates defining caregiver postures for the first three successful trials for each activity/condition combination. A trial was considered successful if none of the reflective markers became occluded for the duration of the trial. The COP (centre of pressure) for each load cell was calculated with respect to the local coordinate reference frame of each load cell and forceplate. These COP coordinates were then transformed into the global reference frame using the coordinates of reflective markers mounted on the load cell and
forceplates. Motion capture data were combined with ground reaction and anthropometric data in a custom biomechanical model adapted from previous studies [120, 253, 254]. Compression at the lumbosacral joint was the primary dependent variable calculated using our biomechanical model for each activity/condition combination. Secondary dependent variables taken from this model were reaction forces estimated at the caregiver's hands and net external moments generated at the lumbosacral joint.

Forces at the caregiver's hands were calculated by finding the vector sum of the reaction forces (ground and bedside) and subtracting the force of gravity acting on the mass of the caregiver. Finally, the resultant hand forces were transformed into a local coordinate frame for the caregiver’s body defined by the vector from the right PSIS to the left PSIS, the vector from midpoint of the PSIS to the midpoint of the ASIS and the vector along the spine from the S1 vertebra to the L5 vertebra to define the medial-lateral, anterior-posterior and vertical directions, respectively.

External moments at the lumbosacral joint were calculated in the global reference frame about all three axes by summing the moments resulting from ground reaction forces at each load cell located at its respective COP as well as the moments resulting from gravity acting on the pelvis, thighs and the lower legs (the foot and shank were considered a single rigid body) using mass and centre of mass (COM) values from the literature [227]. In order to calculate COMs the joint centres of the ankles, knees and hips were needed. The joint centres of the ankles and knees were estimated to be the midpoints of the medial and lateral malleoli and femoral epicondyles respectively [229, 230]. The hip joint centres were predicted using the method used by Seidel et al. [231] and the lumbosacral joint was taken to be 34% of the anterior/posterior distance between the ASISs midpoint and the PSISs midpoint [232]. Finally, the external moments were transformed to the local coordinate system defined previously. Moment arm values used to convert these moments to compression were taken from Chaffin et al. [256] and modified according to recommendations by McGill et al. [168] to increase the rectus abdominis anterior distance by 30% for standing studies.
The modified values are shown in Table 20. For each moment, a single equivalent muscle was used to find the resulting balancing force. The calculations are presented in detail in Appendix B.

The peak compression was determined for each trial and averaged over the first three successful trials. A trial is considered to be successful if all reflective markers remained visible throughout. Similarly, the peak hand forces in the vertical, anterior-posterior and lateral directions were calculated along with the peak external forward bending, side bending and twisting moments for three trials and averaged for each dependent variable.

Table 20. Moment arm lengths used in the biomechanical model

<table>
<thead>
<tr>
<th>Anatomical Moment Muscle Group</th>
<th>Moment Arm (SD) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensor (Extensor Mass)</td>
<td>0.054 (0.004)</td>
</tr>
<tr>
<td>Flexor (Rectus Abdominus)</td>
<td>0.090 (0.018)</td>
</tr>
<tr>
<td>Side Bend (Quadratus Lumborum)</td>
<td>0.074 (0.008)</td>
</tr>
<tr>
<td>Twisting (External Oblique)</td>
<td>0.121 (0.014)</td>
</tr>
</tbody>
</table>

Statistical Analysis

A repeated measures ANOVA was run using SAS 9.1 (Cary, NC) with the single factor of condition with caregivers treated as random blocks for each activity. For activities where a significant effect (p<0.05) of condition was found, the following pairwise comparisons were done to compare the single caregiver condition to both the two-caregiver conditions using the Bonferroni correction for multiple comparisons with p<0.05 as the cut-off for statistical significance:

- Solo condition was compared to the Primary condition
- Solo condition was compared to the Secondary condition

The phases which had significant lumbosacral compression differences between the single and two-caregiver conditions were further investigated by comparing single and two-caregiver conditions for our secondary
outcome variables again using the Bonferroni correction. These follow-up comparisons of external hand forces and external moments at the lumbosacral joint were done to better understand why the single and two caregiver cases differed.

We also calculated the correlation between participant height and peak compression in each activity for both two-caregiver conditions. Since the bed height was set based on our instrumented caregiver’s height, it was possible that the non-instrumented caregiver was put at a disadvantage in cases where the caregiver heights were mismatched. This may have led to the non-instrumented caregiver being unable to provide the same level of assistance for all caregivers.

Finally, for the Roll Right and Roll Left phases in the Solo case, a t-test was done (using the Bonferroni correction and p<0.05 cut-off for statistical significance) to compare the Roll Left and Roll Right activities to determine if there were significant differences in loading resulting from rolling the patient away versus towards the caregiver in the Solo condition. Also, the compression and hand forces from the Primary and Secondary caregivers were compared for the Roll Right and Roll Left activities to determine how evenly loads were shared between caregivers when working in pairs.

7.4 Results

The main finding in this study is that having two caregivers working together to perform sling insertion does not reduce loads on the spine, as highlighted in Figure 34. Figure 35 shows the comparison of single (Solo) and two-caregiver (Primary and Secondary) peak compression at the lumbosacral joint for all eight phases of the sling insertion activity. Loads were found to be on the same order as previous studies and the rolling phases were found to result in the highest load, as in previous work [10, 129]. Significant differences between single and two-caregiver cases were found for five of the eight phases of sling insertion. In all five of these cases,
the compressive loads generated by the two-caregiver cases were higher
than the loads from the single caregiver case. Significant differences were
found for the Roll Right (Primary > Solo), Sling Tuck (Secondary > Solo),
Roll Back (Secondary > Solo), Roll Left (Secondary > Solo) and Roll Back II
(Primary > Solo) phases. The corresponding comparisons of peak hand
forces and external moments at the lumbosacral joint for these five phases
with significant differences indicated (*) are shown in Figure 36, Figure 37,
Figure 38, Figure 39, Figure 40 and Figure 41.
Figure 34. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak compression at the lumbosacral joint for rolling activities. In the Solo caregiver cases, Roll Right refers to rolling the patient away from the caregiver and Roll Left results in the patient being pulled closer to the caregiver. Significant differences (*) if p<0.05.
Figure 35. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak compression at the lumbosacral joint for the eight phases of sling insertion. Significant differences (*) if $p<0.05$. 
Figure 36. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external vertical hand forces for all eight phases of the sling insertion activity. Statistically significant differences are indicated (*) for p<0.05.
Figure 37. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external anterior-posterior hand forces for all eight phases of the sling insertion activity. Statistically significant differences are indicated (*) for p<0.05.
Figure 38. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external lateral hand forces for all eight phases of the sling insertion activity. Statistically significant differences are indicated (*) for p<0.05.
Figure 39. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external twisting moment at the lumbosacral joint for the eight phases of the sling insertion. Statistically significance indicated (*) for p<0.05.
Figure 40. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external side bending moment at the lumbosacral joint for all eight phases of the sling insertion activity. Statistically significant differences are indicated (*) for $p<0.05$. 
Figure 41. Comparison of single (Solo) and two-caregiver (Primary and Secondary) peak external forward bending moment at the lumbosacral joint for all eight phases of the sling insertion activity. Statistically significant differences are indicated (*) for p<0.05.
Correlations between caregiver height and peak lumbosacral compression for the two-caregiver conditions for all eight sling insertion activities are shown in Table 21. None of the correlations were statistically significant \((p<0.05)\) and the magnitude of all correlation coefficients \((r)\) were below 0.6.

Table 21. Correlations between caregiver height and peak compression at the lumbosacral joint in two-caregiver conditions for the eight phases of sling insertion.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Primary Caregiver</th>
<th>Secondary Caregiver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(p) (r)</td>
<td>(p) (R)</td>
</tr>
<tr>
<td>Roll Right</td>
<td>0.76 -0.08</td>
<td>0.51 0.18</td>
</tr>
<tr>
<td>Sling Tuck</td>
<td>0.31 -0.28</td>
<td>0.99 0.002</td>
</tr>
<tr>
<td>Roll Back</td>
<td>0.77 -0.08</td>
<td>0.20 -0.35</td>
</tr>
<tr>
<td>Roll Left</td>
<td>0.57 -0.16</td>
<td>0.29 -0.56</td>
</tr>
<tr>
<td>Sling Unfold</td>
<td>0.64 0.19</td>
<td>0.19 0.35</td>
</tr>
<tr>
<td>Roll Back II</td>
<td>0.40 -0.23</td>
<td>0.66 -0.13</td>
</tr>
<tr>
<td>Leg Straps</td>
<td>0.11 0.43</td>
<td>0.21 0.34</td>
</tr>
<tr>
<td>Connect Straps</td>
<td>0.14 0.40</td>
<td>0.10 0.44</td>
</tr>
</tbody>
</table>

Figure 42 shows an example of a scatter plot of subject height and peak lumbosacral compression for the Primary two-caregiver condition of the Roll Right activity which was representative of our results.
Figure 42. A scatter plot of subject height and peak lumbosacral compression for the Primary condition of the Roll Right activity.

Figure 43 shows the comparison of the Roll Left versus Roll Right phases in the Solo caregiver case (for clarity, the Roll Left and Roll Right activities were renamed Roll Away and Roll Toward, respectively). Our results were different than findings from Zhuang et al.’s [10] previous study which found that rolling patients away from themselves resulted in 9% lower compression than rolling the patient toward themselves. We found the opposite with the Roll Away task resulting in 25% higher forces than the Roll Toward task. We suspect this difference could be due to the inclusion of bedside reaction forces in our calculation which Zhuang et al. did not incorporate. Finally for the Roll Right and Roll Left activities, we examined differences between the Primary and Secondary caregiver. Figure 44 shows the results of this comparison of the peak hand forces applied.
Figure 43. Comparison of the Roll Left versus Roll Right phases in the Solo caregiver case (For clarity Roll Left and Roll Right were renamed Roll Away and Roll Toward, respectively).
Figure 44. Comparison of the internal compression at the lumbosacral joint as well as peak hand forces applied during the Roll Left and Roll Right phases in the two-caregiver conditions.
We found significant differences in the anterior-posterior and vertical peak hand forces between the Primary and Secondary caregivers. The loads applied by the caregiver who was rolling the patient away from herself were higher. That is, the forces were higher on the Primary caregiver working in a pair when the patient actor was being rolled onto his right side and vice versa.

We found significantly higher side bending moments and twisting moments for the Secondary caregiver working in a pair compared to the Solo caregiver during the sling tuck activity. In this case the Secondary caregiver only has to hold up and balance the patient actor on his side while the Solo caregiver is responsible for supporting the patient as well as laying out the sling. Similar to the rolling activities, this activity appears to result in asymmetrical loading resulting in significantly higher twisting and side bending moments for the Secondary caregiver compared to the Solo case. Part of this difference may be due to the Solo caregiver being able to partially support some of their body weight on the patient and on the surface of the bed as they perform this activity.

In both Roll Back activities, the caregiver supporting the patient actor before he is rolled back to supine had significantly higher compression at the lumbosacral joint than the Solo caregiver. As with the rolling and tucking activities, the caregiver with higher lumbosacral compression (the Secondary caregiver in the Roll Back phase and the Primary caregiver in the Roll Back II phase) also had significantly higher twisting and side bending moments compared to the Solo caregiver. In addition, anterior-posterior hand forces for the caregiver working in a pair were significantly higher than for the Solo caregiver.
7.5 Discussion

We were surprised to find that one of the two caregivers working together in the Roll Right and Roll Left activities experienced higher compression at the lumbosacral joint than the Solo caregiver. In both activities, the caregiver standing on the side of the bed from which the patient was rolled away from, (i.e. the Secondary caregiver during the Roll Left task and the Primary caregiver during the Roll Right task) generated higher loads than the Solo caregiver during the same task. In examining the external hand forces and moments at the lumbosacral joint for the Roll Right activity, we found significantly higher twisting moments for both caregivers working as a pair than for the single caregiver. The Roll Left activity shows this same difference in twisting moments but also significantly higher side bending moments for the two-caregiver pair. These findings along with a review of video footage of these trials indicated the explanation for these higher loads in the two-caregiver case are the result of asymmetrical loading of the Primary caregiver for the Roll Right activity and the Secondary caregiver for the Roll Left activity. While the Solo caregiver was able to freely position her body relative to the patient to attain a balanced load, in the two-caregiver case, the force with which the co-caregiver will push is unknown and this unpredictability may lead to the imbalances we measured. We suspect that in some instances, the two caregivers may not be synchronized leading to higher forces from the two partially fighting each other. Future work may consider measuring both caregivers at once to determine if such asynchrony exists. Such a study could also be used to further investigate the effect of a height mismatch between two caregivers.

An important implication of this work is that loads are not always shared evenly. These findings should lead us to question existing guidelines that suggest two caregivers can safely turn a patient that weighs twice as much as a patient a single caregiver can safely turn [257]. Our results indicate that recommendations from the Royal College of Nursing [258], which use more conservative factors when scaling up safe lifting weight where multiple caregivers are involved, are more appropriate. A team of two are limited to
1.33 times the load allowed for a single caregiver and to 1.5 times the load of a single caregiver if three caregivers are available. It is possible that placing multiple caregivers on the same side of the bed as Gonzalez et al. show in their illustrations [257] rather than on either side of the bed could result in more even sharing of loads. These results are applicable not only to sling insertion but also to a number of other activities that involve rolling or turning patients such as inserting bed pans, dressing, use of a hover mat, slider sheets or changing bedding [111, 259].

**Caregiver Staffing Requirements**

The results of this study have important implications for staffing requirements if considered along with the results of our companion study examining single and two-caregiver overhead and floor lift maneuvering. The findings of our lift use study in combination with those from Marras et al. (2009) show that it is safe to allow caregivers to perform the transport phase of a patient transfer (pushing, pulling or turning the lift with patient suspended) alone if there is an overhead lift available, rather than requiring two caregivers to always be present as is currently required. This study confirms that sling insertion can be performed safely by one caregiver with a completely passive 93kg patient.

In practice, lifting activities are not performed in isolation but rather as a series of caretaking activities. A pair of nurses often performs lifting activities one after the other in the morning or evening when patients are taken in or out of bed, along with associated activities such as toileting, dressing, wound care, etc. Therefore, it may be that one or more of these activities would result in higher/unsafe loads on a caregiver if performed alone. However, we feel this study along with our companion study may be used to update regulations governing caregivers to allow for single caregivers to perform lift and transfer activities alone in certain situations rather than dogmatically requiring two caregivers to be present at all times. Such changes to policy may be one way to get a handle on the vicious cycle of caregiver staffing shortages leading to injury and further caregiver
absences, while decreasing cumulative loading on caregivers and reducing risk of injury.

The staffing shortage is expected to grow from 11,000 in 2007 to 60,000 in 2022 in Canada [203]. Similarly, in the US the shortage is projected to grow from over 400,000 in 2010 to over one million in 2020 [204]. This is worrisome considering that the 2005 National Survey of the Work and Health of Nurses reported that caregivers are already under considerable strain at current levels [80]. Sheilds and Wilkins report that 38% of nurses in their survey reported inadequate staffing, 54% said they often arrived at work early or stayed late in order to get their work done. 62% reported working through breaks. 46% said they felt they were expected to work overtime hours. Along with lengthened workday and missing breaks, many caregivers reported being overloaded in other ways. 67% often felt that they had too much work for one person. 45% said that they were not given enough time to do what was expected in their job and 57% said they had too much work to do everything well. In fact, one in eight caregivers felt their team had provided poor patient care. These shortages become a vicious cycle since caregivers working in understaffed units are prone to burn-out faster, making understaffing worse, causing more caregivers to burn-out. However, the Canadian Nurses Association [203] predicts increasing RN productivity by one percent per year would reduce the shortage in Canada to half by 2022 and states this policy would have the best results in the shortest time compared to five other policy scenarios such as increasing enrolment, improving nurse retention, etc. Changing institutional policy to allow single caregivers to perform common activities such as getting patients out of bed in the morning if certain criteria are met (e.g. an overhead lift is available, the patient weighs less than 90kg and are not combative, etc.) could help to address nursing shortages. In such cases the nursing time is not only cut in half, there is an additional savings that come from the time spent tracking down the second caregiver and coordinating with them.
Allowing nurses to work alone in a limited number of situations would have the added benefit of reducing cumulative loading, a risk factor that experts increasingly agree is important [81, 186-190]. For a given number of patients that need to be taken out of bed in the morning, the average cumulative load becomes reduced if a subset of the patients can be transferred by a single caregiver.

**NIOSH Limit**

The peak compression loads when averaged over the 15 caregivers in our study did not exceed the NIOSH limit of 3400N for any phase of the sling insertion activity for either the one or two-caregiver conditions. However, when data from each caregiver was considered individually, 12 of our 15 caregivers exceeded the NIOSH limit during one or more phases of the sling insertion activity. Therefore, while performing a sling insertion with a single caregiver may be no more risky than two-caregiver sling insertion, it should be noted that this still may not be a safe activity. Furthermore, our spine compression estimates may be underestimated by as much as 45% due to our use of the single equivalent muscle model. We are cognizant that the NIOSH limit is protective of 90% of the workforce if a 50/50 ratio of males/females are present [45]. Considering that female cadaver spines were found to withstand only two-thirds the compressive load of male cadaver spines of the same age [183] and 95% of caregivers in Canada are female, we see that the NIOSH limit may not be appropriately applied to this workforce. It may be that sling insertion is inherently unsafe, particularly in a predominantly female workforce, and this activity should be redesigned to reduce the need to roll patients altogether.

### 7.6 Conclusions

The peak compressive loads on a single caregiver were not higher than the loads on either of the two caregivers working as a pair during sling insertion. In fact, loads on one of the caregivers working as a two-caregiver team were higher than the loads on the Solo caregiver for activities when
the patient actor was being turned and when the sling was being tucked under him. Therefore, a single caregiver performing sling insertion under a 93kg patient is at no higher risk of injury than if two caregivers work together. The caregiving community would benefit from changes to policy that allow for single caregiver sling insertion in certain situations. The impact of this policy change would be threefold: reduce cumulative loading on caregivers, increase the efficiency in patient transfer activities and help to address staff shortages. Further biomechanical testing is also needed to determine if other tasks that caregivers perform in pairs can be performed alone such as changing bed sheets and performing wound care activities. However, since 12 of 15 caregivers exceeded the NIOSH limit at some point during sling insertion, it is also important for future work to focus on developing new tools to make sling insertion safer and easier.

Acknowledgements

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Our previous investigation (Chapter 7) found that sling insertion places caregivers at risk of injury, with 12 of our 15 subjects exceeding the safe limit for spine compression. Therefore, the benefits of using a mechanical lift may be offset by the increased risks associated with sling insertion. The need to roll or turn a patient often becomes a barrier to the use of a mechanical lift.

Caregivers need better tools for getting slings under patients. SlingSerter™ may be one such tool. The recently developed device uses compressed air to inflate lifting sleeves effortlessly under a patient. These sleeves are connected to a mechanical lift and the patient is lifted off the bed a short distance allowing a sling to be inserted easily. In many cases, a sling may not be needed at all. A number of patient care activities require that the patient only be lifted a short distance off the bed, such as bedding changes, inserting a bed pan or repositioning the patient in bed. This chapter reports on an initial evaluation of SlingSerter™ by over 60 clinicians to determine how its design might be improved to best serve the needs of caregivers.

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Usability of the SlingSerter™ system: A tool for inserting lifting straps under a patient

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Abstract

Many patient care tasks require positioning items under a patient in bed or repositioning the patient in bed. The SlingSerter™ system uses pressurized air to inflate a set of three or four lifting sleeves under a patient to raise him or her off the bed once connected to a mechanical lift. The usability of the SlingSerter™ system was tested by 61 clinicians. Participants indicated the SlingSerter™ system was less strenuous but more time consuming for some activities such as sling insertion. Ten caregivers were timed while using both the SlingSerter™ system and the conventional method to place a sling under a 116kg surrogate patient. Participants needed an average (SD) of 192 (35)s to insert a sling using the SlingSerter™ system and 40 (7)s with the conventional method. Caregivers agreed the SlingSerter™ system could be helpful to them particularly for challenging patient populations despite the increased time required.

Keywords

Bariatric; Lifting; Patient lift slings

8.1 The problem of lifting patients

The Bureau of Labor Statistics in the United States reported caregivers (including nurses, nursing aides, healthcare workers, etc.) had the highest incidence rates for nonfatal occupational injuries, with hospital and nursing home workers reporting 7 and 8 injuries per 100 full time workers, respectively [260]. In contrast, construction, manufacturing and mining workers reported only 4.6, 4.6 and 2.9 injuries per 100 full time workers,
respectively. The situation is equally alarming in Canada, with 37% of caregivers reporting that they have experienced pain serious enough to prevent them from carrying out their normal daily activities in the past year and more than one in 10 caregivers reporting “severe” or “unbearable” pain [80]. Experts agree that these injuries are due to patient handling activities [74, 75, 87, 218] and that mechanical lifting devices should be used to reduce the risk of injury [10, 90-93, 101, 261].

However, before a mechanical lift can be used, a sling must be positioned under the patient. The conventional method for placing a supine sling under a fully dependent patient involves two caregivers. The patient is rolled onto one side while the sling is folded, placed next to the patient and tucked partially underneath. The patient is then rolled onto his or her other side, allowing the sling to be unfolded. Depending on the type of sling used, a final step of positioning leg straps may be required. For a fully-dependent patient who requires a full body sling, this activity of sling insertion is physically demanding and can increase the risk of injury to caregivers [120, 127].

Sling insertion is often a barrier to lift use. Caregivers report defaulting to manual lifting if the patient has numerous tubes and wires that get in the way of rolling the patient [106]. There have been some attempts at quantifying the loading on caregivers’ bodies resulting from sling insertion [10, 128, 137]. The most rigorous of these studies [137] found compressive loading on the spine to be in excess of the National Institute for Occupational Safety and Health (NIOSH) guideline of 3400N [45]. Santaguida’s study [137] used a 188cm tall 89kg patient actor with a BMI of 25.2kg/m². Zhuang et al. [10] and Silvia et al. [128] did not find that sling insertion exceeds the NIOSH limit, however the patient actors used in these studies weighed considerably less. Zhuang et al. used 77.3kg and 58.2kg patient actors while the patient used by Silvia et al. was 54.4kg. The authors noted the weight of the patient affected the loading on the caregivers’ during the rolling activity. The authors found higher compressive loads were generated when rolling a 77.3kg patient compared to a 58.2 kg patient.
Others have also reported increased loading from heavier patients [110]. We expect that loading on the caregiver will increase considerably when a much heavier, fully dependent bariatric patient must be rolled or turned to insert a sling [111, 112].

The term bariatric is loosely defined as referring to patients who are more than 50kg overweight, have a BMI greater than 40kg/m² or weigh more than 150kg [111]. Ogden et al. [262] estimate that 4.8% of the US population falls in this category, often referred to as extreme or morbid obesity. With a bariatric patient, rolling can be difficult because of excess adipose tissue and limited space on the patient’s bed. Unfortunately, bariatric patient care is an increasingly common issue for caregivers [263].

There is at least one alternative method for inserting slings [111]. Nelson et al. describe a method in which a pair of sliding sheets (sheets of silicon-impregnated nylon) are first inserted under the patient. The sling can then be pulled under the patient in between the two sliding sheets, starting at the patient’s head. Unfortunately, this method still places caregivers at risk of injury due to large push/pull exertions and awkward postures [111].

**SlingSerter™**

SlingSerter™ (Andrew J. Hart Enterprises Ltd., Kleinberg, Ontario) is a novel system that uses pneumatics (compressed gas) to insert a series of lifting sleeves under a patient lying in bed (Figure 45). Figure 46 shows the process of using SlingSerter to place a sling under a patient. These lifting sleeves can be connected to a full-body spreader-bar attached to a mechanical lift and used to raise the patient off the bed a short distance (~10cm). Compressed gas, either air or carbon dioxide (CO₂), at low pressure (70-100kPa), is used to inflate a lifting sleeve stored inside a plastic cartridge. An 18g CO₂ canister (Leland, South Plainfield, New Jersey) is used as the source of compressed gas (hand-held cylinder). Each hand-held cylinder of this size holds enough gas to inflate one lifting sleeve. As it inflates, the lifting sleeve unfurls from within the cartridge and works itself
between a patient and the bed with minimal effort exerted by the caregiver. Once the lifting sleeve is fully inflated, the air supply is disconnected and the plastic cartridge is detached from the lifting sleeve. Both ends of the lifting sleeve have loops for attachment to a stretcher frame spreader bar. The stretcher frame can then be connected to either a floor or overhead lift device. A minimum of three lifting sleeves are required to lift someone off the bed. Typically, the sleeves are placed under the shoulders, hips and just above the knees but more can be used if necessary. Once all of the sleeves have been inflated under the patient and connected to the spreader bar, the patient is raised off the bed a short distance using the mechanical lift. When the patient is off the bed, a number of patient care activities can be performed such as bedding changes, positioning a bed pan or boosting patients up in bed when they have slid down. If the patient is to be lifted out of bed, a conventional sling can also be positioned easily while the patient is suspended above the bed. The system also allows for easy removal of the lifting sleeves once the patient is lowered back onto the bed. The sleeve turns itself inside-out as it is pulled, allowing removal of the strap without friction on the patient’s skin. The process of inflation and removal of a SlingSelter™ sleeve is demonstrated at the end of the YouTube video found here:

www.youtube.com/watch?v=vZPHPYtPkKo [264]

Used lifting sleeves and empty plastic cartridges must be collected and sent out for cleaning, inspection and repacking before they can be used again.
Figure 45. Components of the SlingSerter™ system a) Lifting sleeve  b) Plastic lifting sleeve cartridge (packed) c) Plastic lifting sleeve cartridge (empty) d) Lifting sleeve cartridge attached to the hand-held cylinder and trigger mechanism
Figure 46. The process of using the SlingSerto<sup>TM</sup> system to insert a sling. a) Three lifting sleeves are inflated under the patient. b) The stretcher frame is lowered over the patient, plastic cartridges are removed and the lifting sleeves are connected to the frame. c) The patient is lifted approximately 10cm off the surface of the bed. d) The sling is easily inserted and leg straps are positioned. e) The patient is lowered and the lifting sleeves can be disconnected from the stretcher frame spreader bar. f) The spreader bar is moved away and the lifting sleeves are removed leaving the patient positioned on the sling.
Alternative Embodiments

Three potential embodiments of the SlingSerter™ system were considered. The first embodiment (Figure 45) requires the use of an additional hand-held cylinder for each lifting sleeve to be inserted. Other embodiments include the use of a wall mount bracket which might hold a larger compressed air tank and a number of lifting sleeve cartridges along with a disposal bag for storing used cartridges/sleeves (Figure 47). Another alternative is to use a cart to house a larger compressed air tank, sleeve cartridges and a disposal receptacle (Figure 48).

Figure 47. Wall mount embodiment for the SlingSerter™ system. The wall mounted system will contain a coiled air hose on the left, the compressed air cylinder in the centre and a set of pre-packaged lifting sleeve cartridges on the right. Used components would be discarded in a separate container or bag.
Figure 48. Cart embodiment for the SlingSerter™ system. The base of the cart houses the air cylinders. The inside of the cart is compartmentalized to house pre-packaged plastic lifting sleeve cartridges as well as an area for discarding used components. The cart may be dedicated at the bedside or kept outside the patient room.

**Skin Care**

The SlingSerter™ system has benefits not only for reducing the loads on the caregiver, but also for minimizing chances for skin damage to the patient. Bariatric patients often have skin integrity problems due to excessive moisture accumulation in skin folds. As Camden states, skin problems with obese patients include “…pressure ulcers, candidiasis, delayed wound healing, incontinence dermatitis, and irritation in the intertriginous areas, especially in the presence of co-morbidities, such as diabetes and immobility” [265]. SlingSerter™ is designed to minimize shear forces applied to the skin. During insertion, since the lifting sleeve unfurls as it is inflated, there is no relative motion between the patient’s skin and the lifting sleeve. Similarly during removal, the sleeve again turns inside out, thus minimizing shearing forces between the skin and lifting sleeve. It is also expected that excessive moisture may be prevented from accumulating in the first place if the use of SlingSerter™ leads to an increase in the frequency of lifting and repositioning of bariatric patients.
8.2 Objective

The objective of this investigation was to determine the usability of the SlingSerter™ system through a series of hands-on product testing sessions. Clinicians from a number of clinical settings were shown the system, given the opportunity to try it and surveyed regarding their opinions on the benefits and limitations of the system from both the caregiver and patient perspectives.

8.3 Material and Methods

This investigation was composed of two parts. First, a series of product testing sessions were conducted at four Toronto Rehabilitation Institute clinical sites to get feedback on the use of the SlingSerter™ system and opinions on the alternative embodiments the system could take. Second, a group of caregivers were asked to place a sling under a patient using both the conventional method as well as with the SlingSerter™ system to compare the two methods directly. Both parts of this study were approved by Toronto Rehabilitation Institute’s Research Ethics Board and all participants provided informed consent.

Product Testing Sessions

A total of 61 clinicians participated from four of Toronto Rehabilitation Institute’s sites (University Centre, Lyndhurst Centre, Lakeside Long Term Care Centre and E.W. Bickle Centre for Complex Continuing Care, all located in Toronto, Ontario). Each site specializes in treating different patient populations. Our participants included registered nurses (15), occupational/physiotherapists (11), personal support workers (7), registered practical nurses (RPN) (8), occupational/physiotherapy assistants (8), registered nursing students (5), RPN student (1), PT student (1), as well as a clinical nurse educator, a program services manager, along with three who did not specify their roles. These participants were spread out across the following clinical areas: neuro-rehabilitation (7), geriatric rehabilitation (2),
spinal cord rehabilitation (16), palliative care (3), complex continuing care (23), students not attached to any particular unit (8) with 2 participants not indicating their work site. On average, these participants reporting having 8.6 ± 7.8 years of experience with patient lifting activities. All participants had some front line patient care experience. Exclusion criteria included pregnancy and musculoskeletal or neuromuscular injury of upper limbs, lower limbs, or back within the previous three months.

All participants who fit the inclusion criteria were encouraged to experience the SlingSerter™ system from both the caregiver and the patient’s perspective. The system was used with either a floor lift (Medilifter 4, BHM Ergolift) or an overhead lift (Maxi Sky 440) based on what was available at each site. For all lifts, the standard two point spreader bar was removed and a stretcher frame spreader bar was attached. The stretcher frame spreader bar and Maxi Sky 440 were on loan from ArjoHuntleigh Canada Inc. (Mississauga, Ontario). The Medilifter 4 and BHM Ergolifts were also manufactured by ArjoHuntleigh Canada Inc. but were owned by Toronto Rehabilitation Institute and were available on the clinical units.

A 5.5 gallon Kobalt air compressor (North Wilkesboro, NC) was used as the air supply to save on the cost of single-use hand-held cylinders used. Participants were shown the hand-held cylinders/trigger mechanisms (Fig. 1d) along with renderings of wall mount brackets (Fig. 3) and a cart (Fig. 4) for storing larger compressed gas containers along with new and used lifting sleeve cartridges. Other compressed air options presented included manual hand and foot pumps.

After having had a chance to experience the SlingSerter™ system, participants were asked what they liked and disliked about the system, which embodiments they preferred and which patient types it would be most appropriate for. Feedback was recorded by the researchers as well as on video tape.
Comparison with Conventional Method

Ten female caregivers were asked to perform sling insertion using both the conventional log-roll and SlingSerter™ methods. All participants reported having at least one year of experience in patient lift/transfer activities using mechanical lift devices and on average (SD) had 14.3 (12.0) years of experience. The average (SD) number of lifts they performed per shift was 4.0 (1.6). All subjects were female between ages of 19-60. Exclusion criteria included pregnancy; musculoskeletal or neuromuscular injury of upper limbs, lower limbs, or back within the previous 3 months; medical conditions such as mobility impairment and cardio-respiratory problems.

Slings were inserted under a 116kg, 182cm tall surrogate patient with a BMI of 35. Both methods were performed with the help of the same secondary caregiver, who was a member of our research team. This testing was done in a vacant patient room at the E.W. Bickle Centre for Complex Continuing Care with an overhead lift (Maxi Sky 440) equipped with a stretcher frame spreader bar attached (all supplied by ArjoHuntleigh Canada Inc. (Mississauga, Ontario)), Quick Fit (TIR - L) sling (large size), Carroll hospital bed (Carroll Hospital Group, London Ontario). Again, a 5.5gallon Kobalt air compressor was used as our compressed air source.

Caregivers were asked to adjust the bed to a comfortable working height. Subjects were introduced to the SlingSerter™ system and were asked to practice lifting the surrogate patient using the system with the help of the secondary caregiver until they felt comfortable. The primary caregiver was asked to always stand on the surrogate patient’s left side and the secondary caregiver on the right. Subjects were also given an opportunity to practice the conventional method for two-person sling insertion prior to starting data collection. For our first subject, a coin flip determined which method was performed first (either the conventional method or SlingSerter™ method) and the starting method was alternated for each subsequent test subject to account for order effects.
For the conventional method, the primary caregiver began with the sling folded next to the surrogate patient on the bed. The two caregivers were asked to roll the patient on to his right side. The primary caregiver then folded the sling in thirds and tucked it partially under the patient while the secondary caregiver supported the patient. The caregivers then rolled the surrogate patient onto his left side. The primary caregiver now supported the patient while the secondary caregiver unfolded the sling. The patient was then rolled back to a supine position and finally the leg straps of the sling were placed under the patient’s legs.

For the SlingSerter\textsuperscript{TM} method, the primary caregiver began with three lifting sleeve cartridges laid out on the bed next to the surrogate patient. The primary caregiver was asked to inflate the three sleeves under the surrogate patient consecutively. Next, the primary caregivers detached the plastic cartridges and placed the used plastic parts in a nearby receptacle while the secondary caregiver lowered the ceiling lift with stretcher frame spreader bar attached over the patient. The caregivers then looped the lifting sleeves onto the hooks of the spreader bar and raised the patient off the bed approximately 10cm. The two caregivers then placed the sling under the patient, positioned the leg straps and lowered him down. Finally, the lifting sleeves were detached from the spreader bar, removed by the primary caregiver and placed in the used material receptacle.

Caregiver subjects were asked to perform the first method from start to finish three times each before switching to the final method. The surrogate patient was asked to return to a supine position in the middle of the bed with his arms at his sides at the beginning of each new trial. All trials were timed using a stopwatch and video-taped. Caregivers were asked to indicate their ratings of perceived exertion based on the modified Borg scale \cite{134} for each method at the end of the testing session. Participants were also asked which method they preferred overall and whether they would consider using the SlingSerter\textsuperscript{TM} system, in its current form, in their clinical practice.
8.4 Results

Product Testing Sessions

Overall impressions of the SlingSerter™ system were very positive. Many participants stated that this system could make their jobs “much easier” and “would save our backs” because front line workers often “get exhausted with all the lifting”. Users found inflating the lifting sleeves to be very easy. However, nearly all participants had difficulty sliding the plastic collar down to release the plastic cartridge from the lifting sleeve.

Participants who played the role of the surrogate patient mostly said they found it comfortable to be lifted using three lifting sleeves, although many commented that they felt too much strain on their necks and that some form of head support was needed. Clinicians in the surrogate patient role also reported the stretcher frame came down too close to their faces and made them feel claustrophobic. Most agreed that patients are often uncomfortable with things hanging over them. This discomfort is common with the use of a stretcher frame spreader bar following conventional sling insertion. Some participants thought the surrogate patients were at risk of hitting their heads on the spreader bar since it came so close to their forehead when 110cm length lifting straps were used. Surrogate patients also reported some shearing forces when the sleeves were removed as the sleeves didn’t always turn fully inside out. Nearly all participants agreed that the SlingSerter™ system was well suited for inserting slings under bariatric patients. However, some were concerned about possible discomfort of a set of lifting sleeves on a bariatric patient’s excess adipose tissue.

Participants also suggested other patient populations such as patients with paralysis or contractures, stroke or head injury that cannot assist with rolling, uncooperative patients, those with hip or knee pain or those who cannot be turned could also benefit from SlingSerter™. In addition, participants thought the device could be useful for activities other than inserting slings. For example, a single lifting sleeve connected to a
mechanical lift could be used to support single body parts for wound care, a pair of sleeves could be used to help insert a bed pan or a full set of sleeves may be used to support a patient during bed linen changes or for repositioning patients in bed, a task that is known to be unsafe [110].

Most clinicians preferred the wall mounted embodiment for the SlingSerter™ system to the cart or hand-held cylinder. None expressed a preference for the hand-held cylinder and many commented the wall mounted version would be the least obtrusive in the clinical environment. It was generally agreed that it would take too long to change the hand-held cylinders for each lifting sleeve to be inflated and that there would not be enough space at the bedside to store the cart. Further, it was agreed that whichever compressed gas source was used, that it should hold enough for a day’s worth of lifts.

Conventional Method

Participants required an average (SD) of 192 (35)s to complete a sling insertion using the SlingSerter™ system while it only took 40 (7)s to insert the sling using the conventional method. The participants’ ratings of perceived exertion indicated that using the SlingSerter™ system was less strenuous than the conventional method. The average (SD) rating for the conventional method was 4.6 (0.5) while the SlingSerter™ system was 1.0 (2.6). Seven of the 10 subjects preferred the SlingSerter™ method to the conventional method and nine of the 10 subjects said they recommend that the system be introduced into clinical practice. Five of our 10 subjects commented that removal of the lifting sleeves could be difficult at times, particularly the one placed under the hips.

8.5 Discussion

The primary finding of this investigation is that the prototype SlingSerter™ system could be a useful tool to clinicians despite the increased time needed to use it. However, there are a number of improvements that should
be made before introducing it into clinical practice including making it easier to detach the plastic cartridge, making the stretcher frame spreader bar less claustrophobic, examining the comfort of the existing lifting sleeves for bariatric patients and improving lifting sleeve retraction so that there are no shearing forces on the skin when the sleeve is removed.

The difficulty in detaching the plastic cartridge is the result of the caregiver having to squeeze a pair of tabs on the side of the plastic cartridge while simultaneously sliding the collar down. The collar is tightly fitted around the plastic cartridge to reduce the chance of air leakage. The process of removing the collar can be made easier by developing a quick release mechanism that would still allow for a tight seal during inflation but require less effort to detach. Similarly, the claustrophobic feeling caused by the stretcher frame spreader bar coming too close to the surrogate patient could be addressed either by lengthening the lifting sleeves or by changing the design of the spreader bar to be less obtrusive near the patient’s head. This would also reduce the risk of head injury to the patient. These suggestions have been communicated to the manufacturer and the system is being improved.

Andrew J. Hart Enterprises Ltd. is currently developing an alternative custom eight-point spreader bar designed to be used with the SlingSerter™ system to replace the stretcher frame spreader bar used in this study. The objective of the new design is to function as a standard two or four point spreader bar that also has the ability to fold out to become a six or eight point spreader bar. Such a design would allow most patients to be lifted with a conventional sling/sling insertion method using the two point spreader bar. It would also allow for quick conversion to the six or eight point configuration for bariatric and/or other special patient populations to be lifted with the help of the SlingSerter™ system.

Another concern raised during our product testing sessions was whether the existing lifting sleeves would cut into adipose tissue of bariatric patients making the use of SlingSerter™ uncomfortable. To date, the system has been used to insert lifting sleeves under a simulated 250 kg patient. This
weight was simulated by stacking 114kg, 91kg and 45kg researchers on top of one another. However, this was not representative of a true bariatric patient due to a lack of adipose tissue. Further testing with larger patients is needed to determine whether the performance of the current lifting sleeves is suitable for use with bariatric patients. Possible solutions might include increasing either the sleeve width or the number of sleeves used.

A final problem with the SlingSerter™ system had to do with the removal of lifting sleeves. The sleeves did not always turn inside out fully. This resulted in the sleeve bunching up and being dragged out from under the surrogate patient increasing the chance of skin damage. Based on subsequent testing, we determined this problem was caused by a high coefficient of friction of the inner surface of the lifting sleeve. Pilot testing with baby powder in the sleeve improved sleeve retraction. Further testing with new materials is needed to determine if this problem can be eliminated and to determine how much the strap removal force will increase as the patient gets heavier.

Results from the comparison of SlingSerter™ and conventional sling insertion methods showed that using SlingSerter™ appears to be less strenuous on the caregiver; however, it takes considerably longer than the conventional rolling method. We expect the same trade-off to be present for other activities such as positioning a bed pan, changing bedding or boosting/repositioning patients up in bed. However, the extra cost associated with the additional time may be balanced by the savings incurred from needing less caregivers to lift large patients. We should consider not only the time required for the task to be completed but also the time required for these extra caregivers to coordinate their schedules to be present in the patient’s room together. Finally, we note that the time to use SlingSerter™ could increase in practice depending on the source of compressed gas chosen. For instance, if the hand-held cylinders are used, the additional delay of replacing the cylinder for each strap should be included. Similarly, the choice of cart based or wall mounted device could affect the set up time needed to use the device and therefore could be an
important factor in determining whether such a device gains acceptance clinically. Further testing with heavier bariatric patients with the next generation prototype is needed in order to gain a full understanding of the time requirements for use.

8.6 Conclusion

Caregivers that tested the SlingSerter™ system generally agreed it would be a welcome tool in clinical practice, although there were some design changes that should be implemented before full production makes clinical use easier. To minimize the extra time needed, clinicians tended to prefer a wall-mounted embodiment for the system. Clinicians agreed that SlingSerter™ would be useful for inserting slings under bariatric patients and other special patient populations who are challenging to turn. Other applications thought to be suited to SlingSerter™ are those where the patient is lifted a short distance off a bed such as positioning bed pans or changing bedding. The SlingSerter™ system was found to take nearly five times longer to insert a sling compared to the conventional method with a 116kg patient, however the perceived exertion on caregivers was considerably less and the majority of caregivers stated that they preferred the SlingSerter™ system overall. We expect the costs associated with the increased time required to use SlingSerter™ may be balanced by reduced personnel requirements for bariatric care tasks. Further testing with bariatric patients is needed.

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Disclosure Statement

Three of the authors (TD, ECK, and GRF) are inventors of the SlingSertor™ device. A patent has been applied for and the product is not currently commercially available. Andrew J. Hart Enterprises Ltd. is our commercial partner for this product.
9 Cumulative Load

The findings of the studies discussed in chapters 5, 6 and 7 lead us to the conclusion that it is safe to allowing caregivers to perform patient lifting activities alone with an overhead lift. New tools, such as SlingSerter™ (Chapter 8) could be helpful to caregivers by reducing peak loads. However, the effects of such chances to a caregiver’s cumulative load remain unknown. Our hope is that relaxing the requirement to have two caregivers present for all patient lifting activities would reduce a caregiver’s cumulative exposure. However, we do not know how caregivers will use their extra time and therefore they could increase their cumulative load. Similarly, we suspect reducing peak loads associated with sling insertion is beneficial however, since it takes considerably longer to use SlingSerter™, we are unsure of the effect on cumulative loading. Unfortunately, measuring cumulative load is difficult with current techniques. The work presented in this chapter evaluates a novel method for estimating cumulative loading by measuring spine shrinkage.

The manuscript is not yet published but will be submitted to Applied Ergonomics shortly.
Spine Shrinkage and Cumulative Load During Sitting and Standing

Tilak Dutta

Abstract

There is increasing agreement that back injuries are the result of cumulative loading on the spine over a period of time as opposed to a large one-time load. Unfortunately, it is difficult to estimate cumulative loading of the spine using conventional methods. This investigation considers whether measuring small diurnal changes in height with a stadiometer can be used to estimate cumulative load in the workplace. Nine healthy participants were asked to perform seated and standing desk work while wearing a weighted vest (either weighted with 10% of the participant’s body mass or unweighted) while precise height measurements were taken every hour for four hours using a stadiometer. Results indicated there was a significant difference between the loaded and unloaded conditions for both seated and standing cases. There was also a significant difference between seated-loaded condition and the standing-loaded condition. This difference between the two loaded conditions indicates that spine shrinkage is dependent on posture. Therefore it is not possible to estimate cumulative loading from height change alone.

Keywords

Spine shrinkage, stadiometer, cumulative loading

9.1 Background

Caregivers (including nurses, nursing aides, and other healthcare workers) sustain injuries in the workplace at alarming rates. They have higher rates
of injury than other occupations traditionally considered hazardous such as mining, construction and manufacturing [101]. In particular, the prevalence of back injury is high [9, 10]. According to a survey of the work and health of nurses, 25% of nurses in Canada had experienced a back injury in the previous year [80]. The situation is no better in the US where 52% of nurses complain of chronic low back pain [8] and 38% of nurses suffer from back pain severe enough to require time off work [266].

Ongoing attempts to address this problem have focused on reducing the peak loads associated with a given task. Load limits have been established, such as the National Institute for Occupational Safety and Health (NIOSH) limit which states that the maximum weight that can be lifted is 16kg [87]. Mechanical lifts were introduced to reduce the loads experienced while lifting and transferring patients. ‘Zero-lift’ policies, which restrict manual lifting, followed in many institutions to ensure caregivers were using the lift devices. Unfortunately, we continue to see very high rates of back injury. The problem may be that caregivers now perform more repetitive, sustained lifting with these lighter loads [195]. This could result in higher cumulative loading over the day which experts now agree will increase the risk of back injury [186-190]. Cumulative load is the integral of force over a given time period (which gives the area under a force vs. time plot).

This emerging view is based on the theory that the structures of the low back deform in a time-dependent manner, causing thresholds for tolerance to be altered by prior loading. The first evidence of the importance of cumulative load was provided by Kumar who showed a relationship between cumulative load and back pain in health care aides [186]. Norman et al. presented epidemiological evidence that cumulative moment and cumulative forces measured at the hands could be used to “[distinguish] those who report [low back pain] in the workplace from those who do not” [187]. Winkel and Mathiassen agree, suggesting that evaluations of mechanical exposure should be characterized not only by amplitude (the magnitude of force) but also duration and repetitiveness of the movement [193]. In another study, Daynard et al. found that while mechanical lift
devices did reduce peak loads, in some cases cumulative load was increased [189]. The authors point out that the focus often falls on peak forces because it is a more tangible measure. “Personnel feel reductions in peak forces...” while the benefits of reducing cumulative loading are only seen long-term [189]. In a similar study, Santaguida et al. found that the use of overhead lifts resulted in lower cumulative loads than the use of floor lifts [137]. Finally, in a study of sheep shearers, Gregory et al., found that while acute loads do not exceed the NIOSH limit, the cumulative loads were very high due to extreme postures that were held for extended periods and that this likely explained the high rates of back injury with these workers [194].

Unfortunately, research into establishing a threshold limit value for cumulative spine loading has been slow to evolve despite the apparent importance of measuring cumulative load for determining risk of low back injury [151]. Germany has been progressive in this regard and has defined a recommended dose limit of 19.8MN per shift [196]. However, the validity of this dose limit has yet to be demonstrated [191]. The lack of progress on cumulative load limits is partially due to the difficulty of estimating cumulative load exposure using existing biomechanical methods. Two sets of data are needed to calculate the load on the spine: (i) body posture data and (ii) loading data. Traditional motion capture and force plate systems require the subject to remain in one place. Perhaps such a set-up is reasonable for an assembly line worker who stands in one place but it cannot capture a caregiver’s activities as he or she moves from room to room. Without a loading profile for the entire day, it can be difficult to draw useful conclusions. For instance, if a task is redesigned so that it can be completed faster, the cumulative load associated with that task will be reduced. However, if the caregiver performs additional tasks with this extra time, there may not be any net benefit. For this reason Fischer et al. point out that time standardization is needed for cumulative load estimates to be useful [197] and ideally, cumulative load needs to be measured over the entire workday.
Another drawback of existing measurement methods is that the underpinning biomechanical models are incomplete. They do not account for antagonistic co-contraction of abdominal muscles and they use average values for the lengths of muscle moment arms, resulting in sizable errors in loading estimates [7]. Kingma et al., found that loading estimates from different models could vary as much as 25%, depending on whether a linked segment model or an EMG assisted model was used [163]. This underestimation may take on greater importance now that we will be taking an integral than it did when we were only concerned with peak values. Although, it is unclear if the simple integral of cumulative load should be the metric of interest or if loads associated with different activities must be weighted by factors that account for a change in the risk of injury [191].

A more complex biomechanical model is needed, one that includes measurements of EMG signals from the trunk and back muscles to reduce these errors. Measurements of this complexity are only practical in the laboratory. Unfortunately, we know that there are environmental and psychosocial factors that can affect the way caregivers do their jobs that cannot be reproduced in the laboratory environment. It has been shown that these psychosocial factors can directly affect spinal loading [187, 209, 210, 267].

Therefore, there is a need for a better method for estimating biologically relevant cumulative loading in the field over a caregiver’s workday. The measurement of spine shrinkage may provide the opportunity to develop just such a method.

**Spine Shrinkage**

During the day, water is forced out of the intervertebral discs as the spine is placed under axial compressive loading. This water loss causes the spine to decrease in length [33]. Water re-enters the spine at night when we lay down. The circadian variation of height can be as much as 1.1% of a person’s stature [268]. Tyrrell et al. determined that 54% of the diurnal loss in
stature happened in the first hour after rising and that 70% was regained in the first half of the night [268].

Research has shown that spine shrinkage is related to loading on the spine [269]. Althoff et al. showed that spine shrinkage is linearly related to the quasi-static load [200]. Au et al. showed that twisting tasks resulted in more spinal shrinkage compared to lateral or flexion motion tasks [270]. Fowler et al., looked at the differences between walking with a heavy mailbag and without [271]. Dowzer looked at spine shrinkage due to running in shallow water compared to conventional running [272]. Others have explored differences in spine shrinkage among those with and without back pain [273, 274] or among subjects with differing body mass [275]. Leivseth and Drerup compared seated and standing work [276]. The most comprehensive spine shrinkage study to date is that by McGill et al. [201]. They performed three experiments, all focused on understanding the relationship between loading and spinal shrinkage. The first study concluded there was no difference in performing spine shrinkage measurement with subjects sitting or standing. The second study compared static and dynamic lifting activities. The third study considered the effect of work/rest cycles. Findings in the latter two investigations were inconclusive due to subject variability. Even so, McGill et al. state “[w]hile subject variability (and perhaps biological variability) is a liability, it may be feasible to develop load time integrals for load exposure in the future, since the asset of the spinal shrinkage approach appears to be that it is one of the few available techniques to assess cumulative loading for both isometric postures, prolonged sitting, repeated tasks and responds to the positive adaptive changes that occur from periods of rest ... [I]t would appear that more quantification of the relationships that modulate spinal shrinkage are required to account for the variance in stature measurements”.

Other researchers have tried to take advantage of spine shrinkage for its ability to account for the restorative property of rest breaks that McGill et al. (1996) identified. For instance, Beynon and Reilly showed that a 20-minute seated break led to greater recovery in stature compared to a 20-
minute standing break during a four-hour bout of simulated nursing activity [277]. Similarly, Haker et al. noted that lying down for rest breaks is more restorative than sitting [278]. And Helander et al. showed that workers taking 20 or 40 minute standing/walking breaks had less spine shrinkage during four hours of seated work compared to those who remaining seated during the breaks [32].

The relationship between cumulative load and spine shrinkage has only been explored in a limited way to date. The objective of this investigation is to address the variability encountered in previous work by controlling activity level and hydration to determine if there is a simple relationship between cumulative loading and spine shrinkage.

To measure small changes in height we will use a stadiometer (Figure 49). Stadiometers consist of a rigid frame, mounted at a right angle to a base plate such that it places the subject at a 75° head up tilt. A high-resolution linear variable displacement transducer is used to detect changes in height by measuring vertical displacement.
Figure 49. The stadiometer used in this investigation
9.2 Methods

A stadiometer was constructed based on the design by Healey et al. [279] and was used to measure spine shrinkage of nine healthy subjects all between the ages of 20 and 30 over five non-consecutive days.
Table 22. The four measurement conditions measured for each subject over four days

<table>
<thead>
<tr>
<th>Training day</th>
<th>Day 0</th>
<th>Day A</th>
<th>Day B</th>
<th>Day C</th>
<th>Day D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seated deskwork</td>
<td>Seated deskwork</td>
<td>Standing deskwork</td>
<td>Standing deskwork</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unweighted vest</td>
<td>10% body weight vest</td>
<td>Unweighted vest</td>
<td>10% body weight vest</td>
<td></td>
</tr>
<tr>
<td>2 hrs</td>
<td>4 hrs</td>
<td>4 hrs</td>
<td>4 hrs</td>
<td>4 hrs</td>
<td>4 hrs</td>
</tr>
</tbody>
</table>
The first day (Day 0) for our study was used to familiarize subjects with the process of taking measurements with a stadiometer. Participants were asked to drink at least 1L of water before going to bed on days prior to measurement days (days A, B, C and D). They were also asked to drink at least another 500ml prior to coming into the lab on a measurement day and to arrive as early in the morning as possible. The quantity of water intake was designed to ensure individuals were adequately hydrated over the duration of the measurement session.

On measurement days, participants were asked to assume the Fowler recovery position (Figure 50) for 20 minutes upon arrival at our laboratory. Adopting this position established a baseline for the experiment by eliminating any abnormal spinal loading experienced prior to the participant’s arrival [279]. Participants were then asked to perform desk work either seated or standing while wearing a vest weighted with either nothing or 10% of their body weight. The four conditions are shown in Table 22. Spine shrinkage was measured hourly over a four-hour period in the morning using the stadiometer similar to previous work [32, 277]. For days on which the participant was seated, an office chair adjusted to the participant’s comfort and the participant was provided a workstation with a desk, computer and phone. When participants were required to stand, the workstation was modified by raising the surface of the desk so that the monitor, keyboard, mouse and phone to a comfortable height (Figure 51). A latin square design counterbalanced for sequential effects was used to determine the order of Days A, B, C and D. The weighted vest was removed for height measurement so that posture in the stadiometer was consistent and participants were asked to put the vest back on immediately after the measurement was completed.
The stadiometer consisted of a rigid frame, mounted at a right angle to a base plate such that it places the subject at a 75° head up tilt and a Novotechnik TS50 linear displacement potentiometer (Figure 49). The following five points of the subject’s body were supported in the stadiometer: (i) the most posterior point on the head; (ii) the deepest point of cervical lordosis; (iii) the most prominent point of thoracic kyphosis; (iv) the deepest point of lumbar lordosis; and (v) the buttocks at the sacral crest.
For each set of measurements, the subjects were asked to stand in the stadiometer for two minutes to allow for heel pad compression [280]. The probe from the potentiometer was positioned to lie directly above the apex of each participant’s head making contact with the scalp. The position of the head was controlled using a pair of spectacle frames worn with two laser pointers attached. The subject is asked to align the laser beams with marks on a projection panel overhead using a mirror placed at eye level [279, 281]. Five consecutive stature recordings were taken to reduce the influence of minor variations caused by breathing phase or involuntary movements with each reading taken at the end of an exhalation [33].

For each set of five height measurements from the stadiometer, an average height change was calculated. The average height change from the baseline height on days A, B, C and D was plotted on a height change vs. time graph for each test day. The mean height change at the four hour time point was calculated for each of the four conditions. The following comparisons were performed with the *t* test function in Matlab using the Bonferroni adjustment for multiple comparisons and *p*<0.5 as the cut-off for statistical significance:

i) loaded-seated vs. unloaded seated

ii) loaded-standing vs. unloaded standing

iii) unloaded-seated vs. unloaded standing

iv) loaded-seated vs. loaded-standing
9.3 Results and Discussion

Figure 52 shows changes in height over four hours in each of the four conditions for a typical participant and Figure 53 shows the mean height changes recorded for all subjects at the four hour time point.

From Figure 53 we can see that spine shrinkage was greater for the two loaded conditions than the unloaded conditions and that the unloaded conditions did not differ from each other, as expected. The figure also shows that the standing-loaded case had greater shrinkage than the seated-loaded case. If spine shrinkage was a representation of cumulative load, we would expect shrinkage to be the same in both loaded conditions.

We cannot say what caused the decreased shrinkage in the seated scenario. It may be that the seated posture allowed the spine an opportunity to unload enough for some rehydration of the intervertebral discs. It may also be the difference was due to the hourly change in posture participants got on the ‘seated’ days during their stadiometer measurements. Results of previous studies indicate either of these may be the case. Taking seated breaks has been shown to result in height rebound compared to standing breaks during standing work [277]. Taking standing/walking breaks has also been shown to be beneficial for seated work. However in this latter study, standing/walking breaks of five and ten minute duration did not show rebound in stature. Rebound was only seen after breaks of 20 and 40 minutes [32]. In our case, subjects got the equivalent of a 3-4 minute standing break during seated conditions while height measurements were done using the stadiometer. According to Helander et al., this should not have resulted in rebound. A follow-up study is needed with a seated stadiometer that has been shown to be just as accurate as a standing stadiometer [201].
Figure 52. Height change for a representative participant

Figure 53. Mean height change after four hours
These findings indicate that spine shrinkage is dependent on posture and therefore estimating absolute cumulative load from height change alone is not possible. However, these findings confirm previous findings that seated postures cause less spine shrinkage than standing. Therefore caregivers should be encouraged to take every opportunity to sit during their workday (when conversing with patients for instance) as 20 minutes of sitting has been shown to result in significantly less spine shrinkage over a four hour nursing shift [277].

Furthermore, spine shrinkage may lead us to a better understanding of how to assess the risk of injury from estimates of cumulative load. Cumulative load estimates that are the result of simply integrating force over time assume loading from all activities increases the risk of injury equally. But, intuitively we expect a worker standing in a neutral posture or sitting during a break is not increasing his or her risk of injury. In fact, we suspect workers can experience some restorative effects even though there is some load on the spine. Therefore, we need a method of determining which types of loading are ultimately injurious and which are restorative and therefore reduce risk of injury. Based on the results of cadaver studies [180] Jager et al. argued that doubling force has more injurious effect than doubling exposure time, so the two factors should not be equally weighted [199]. Jager et al. suggest squaring the force values or even raising them to the fourth power to more heavily weight the importance of higher loads compared to baseline loading. Unfortunately, the epidemiological relevance of these suggestions are unknown [191]. Waters et al. suggest developing a series of force multipliers based on epidemiological evidence or in-vitro studies [191]. However, we may require a formula more complicated than the simple multiplier proposed by Waters et al. We have seen from this and previous studies, activities such as standing may be helpful or harmful depending on preceding activities. Developing these activity weightings may be complicated because they will have to incorporate a term to account for the nature of previous loading. While spine shrinkage may not be able to measure cumulative loading directly, it may provide insight in the
complexities of understanding how we can best use cumulative loading to assess risk of injury.

9.4 Conclusions

Seated-loaded and standing-loaded conditions resulted in significantly different amounts of spine shrinkage after four hours. Therefore, we conclude it is not possible to estimate cumulative loading from height change alone. However, the technique may still be useful for determining the relative increase to the risk of injury from different activities. These results support previous findings that caregivers should take seated breaks.
10 Discussion

This section discusses how our findings relate to the three hypotheses for why back injuries remain a problem in caregiving. Recall our work focuses on H2. Our three hypotheses are repeated here for reference:

H1: Caregivers do not always use mechanical lifts for patient lifting activities.

H2: Some patient lifting activities done using mechanical lifts result in unsafe loading on a caregiver’s spine.

H2.1.1: Floor lifts result in higher loading than overhead lifts.

H2.1.2: Two caregivers operating a floor lift result in lower loading on caregivers than a caregiver working alone.

H2.1.3: Two caregivers operating an overhead lift result in lower loading on caregivers than a caregiver working alone.

H2.2.1: More-experienced caregivers are exposed to lower loading than less-experienced caregivers when operating a floor lift.

H2.2.2: More-experienced caregivers are exposed to lower loading than less-experienced caregivers when operating an overhead lift.

H2.3.1: Sling insertion result in loading of the spine in excess of the 3400N safe limit for spine compression.

H2.3.2: Two caregivers performing sling insertion experience lower loading than a caregiver working alone.

H2.4.1: Using SlingSerter™ to perform sling insertion takes longer than using the conventional sling insertion method.

H2.4.2: SlingSerter™ has the potential to reduce loading on caregivers.
H2.5: Spine shrinkage can be used to estimate cumulative compression of the spine.

H3: Activities other than patient lifting result in loads in excess of the 3400N NIOSH limit for spine compression or the 1000N spine shear limit.

Mechanical Lift Use

Our first finding (addressing H2.1.1) was that using overhead lifts results in lower loading on caregivers than using floor lifts. Having two caregivers operate a lift together resulted in significant reductions in loading compared to the single caregiver case for both floor (H2.1.2) and overhead lifts (H2.1.3). However, when operating a floor lift, the magnitude of the difference between the single caregiver condition and one of the two caregiver conditions remained small even though it may have been statistically significant. We found floor lifts were unsafe when operated by two caregivers but overhead lifts were safe to be used by caregivers working alone by combining our finding with previous work.

Further, we found that less-experienced caregivers generated higher loads with floor lifts than more-experienced caregivers (H2.2.1) while this difference was not present with overhead lifts (H2.2.2). This suggests overhead lifts are more suitable for new caregivers as there is more of a learning curve with floor lifts. While our focus was on the clinical environment, we note it is particularly important to use overhead lifts in the home environment where carpeting and thresholds would create additional resistance to the movement of a floor lift and it is more likely to find a less-experienced informal caregiver. A limitation of this study was that we did not control for age. We found a statistically significant difference between the ages of our more-experienced and less-experienced groups. Therefore, it is possible that the differences we note may have been the result of age related differences rather than experience or some combination of the two factors. Therefore, to be more precise we should
describe the differences in loading we found to be between older, more-experienced workers and younger, less-experienced workers. However, the impact of this finding remains the same as younger, less-experienced caregivers may be at disproportionately higher risk of injury when using floor lifts.

Allowing a caregiver to operate lifts alone with overhead lifts means that a considerable amount of caregiving time may be saved as these activities can be performed without the need for a second caregiver. Unfortunately, most health care institutions require two caregivers to be present when any lift is used.

We think a revision of institutional policy allowing single caregivers the ability to perform patient lifting activities alone, if an overhead lift is available, would be an incentive for installation of overhead lifts rather than floor lifts. Before such policy can be implemented, single caregiver lift use needs to be reviewed further. First, a list of circumstances under which caregivers could safely work alone must be compiled. For instance, the patient must be cooperative, under a certain body weight etc. Second, changes to cumulative loading and daily workload need to be considered to ensure these changes will reduce overall risk of injury without other negative effects.

This strategy addresses H1 not only by motivating the installation of more lifts, but also because we avoid one of the most commonly reported barriers to lift use. Caregivers will no longer have to go searching their ward for the floor lift if the lift is always on the track in the room [80, 106].

There are a minority of circumstances where overhead lifts cannot be used because tracks cannot be installed everywhere. Therefore there is still a need for a better floor lift which may include powered manoeuvring capabilities. We are aware of one such device [282].
Sling Insertion

We also found a caregiver can perform sling insertion alone without experiencing any higher loads than two caregivers (H2.3.2). Therefore allowing for single-caregiver-lifting could afford caregivers considerably more flexibility and allow caregivers more control over their workday hopefully leading to lower workload and less strain. However, while a caregiver performing sling insertion alone is at no higher risk of injury, we note that the majority of our participants (12 of 15) exceeded the safe limit of 3400N for spine compression (H2.3.1) and therefore sling insertion cannot be considered a safe activity in general.

We should keep in mind these results are based on a caregiver working with a standard hospital bed that can be raised to comfortable working heights. The situation will be different in the home environment where beds tend to be lower/wider and force caregivers to bend further.

SlingSerter™

Since the activity of inserting a sling is unsafe, caregivers may benefit from tools such as SlingSerter™. This tool removes a further barrier to mechanical lift use – the need to roll the patient to get a sling inserted (again addressing H1) [106]. We also expect that SlingSerter™ will make it easier to use lifts for activities that are currently done manually. For instance, SlingSerter™ may allow lift use for inserting bed pans, changing bedding and repositioning patients in bed.

Sling insertion using SlingSerter™ was more time consuming than manual sling insertion with our 116kg surrogate patient (H2.4.1). However, we expect the extra time will be balanced by reduced personnel requirements as the patient weight increases. In fact, clinicians felt SlingSerter™ had the potential to reduce loading particularly for use with bariatric patients as well as other challenging patient populations (H2.4.2). Further testing with bariatric patients is needed with the next generation prototype of SlingSerter™. A key question remaining is how many lifting sleeves are
needed to comfortably lift patients of varying size. Also, we will need to investigate how a chosen embodiment to house the compressed air source and cartridges will fit into clinical practice.

**Cumulative Load**

We found that spine shrinkage cannot be used to directly estimate cumulative load (H2.5). However, the current understanding of the role of cumulative load in preventing injury is in its infancy. And although spine shrinkage cannot be used to directly estimate cumulative load, it still has the potential to provide valuable information. Waters et al. list a number of important issues that must be addressed before measures of cumulative load are relevant to preventing injury in caregivers or workers in general [191, 192]. They include the need to:

- Develop better methods of recording posture
- Determine which spinal parameters (compression, shear, moment) best predict risk of injury
- Determine epidemiologically relevant load integration methods
- Develop and validate an evidence-based dose limit for cumulative load that appropriately accounts for repetitiveness, magnitude and duration of exposure

Spine shrinkage may provide useful information for the final two points. Recall (section 1.2) that our bodies produce an inflammatory response to instability in the spine caused by micro-damage to tissues. Muscular hyper-excitability sometimes follows to add stability to the spine and prevent further damage. In individuals with underlying complications, this muscle tightness can lead to an episode of acute back pain. Further study is needed to determine if there is a relationship between spine shrinkage and inflammation.

Once this field matures, it will help us to better address H3 and how the varieties of activities caregivers perform contribute to their risk of back injury. Likely we will still need peak loading limits to prevent endplate
microfractures. However, cumulative load limits will prevent inflammatory-response-related episodes of acute back pain.

**Education**

Finally, my experience with this project has convinced me that one of the most important reasons caregivers hurt their backs is the general misunderstanding of the limits of the human spine. As a first step, we have created a website [283] with a short YouTube video [264] that highlights the following fundamental points:

1. Manual lifting of patients is unsafe. Lifting more than 25kg on a regular basis leads to the accumulation of microscopic damage to the spine with no pain or discomfort in the short term.
2. Mechanical lift devices do not remove all risk of injury. In particular maneuvering a floor lift, either with one or two caregivers is unsafe. Overhead lifts should be used whenever possible.
3. Regardless of the type of lift you use, placing the sling under the patient is unsafe, either with one or two caregivers.

The target of this message is not only to address H1 and convince caregivers they should always be using mechanical lifts. It is important to inform the general public as well. Many of us will end up caring for another person at some point in our lives as informal caregivers. Understanding what our backs are capable of should keep us all safer.
11 Conclusions

The findings from all investigations in this work are summarized here:

1. Overhead lifts are preferable to floor lifts. Two caregivers working together with a floor lift did not reduce loads on the primary caregiver in a meaningful way compared to the single caregiver case. A single caregiver operating an overhead lift experienced lower loading than two caregivers operating a floor lift. Floor lifts were found to have a steeper learning curve. Less-experienced younger caregivers generated higher loads than their more-experienced, older counterparts with floor lifts while this effect of experience and/or age was not present with overhead lift use.

2. A single caregiver is at no higher risk of injury performing sling insertion than if two caregivers worked together with a 93kg patient. However, the traditional method of sling insertion is not safe as 12 of 15 caregivers exceeded the NIOSH limit during the task.

3. Caregivers determined SlingSerter™ would be a welcome tool in clinical practice to help with placing slings under bariatric patients and other challenging patient populations. The system could also be useful for other activities that require patients to be lifted a short distance off a bed. A number of design improvements are needed before the device is ready for clinical use.

4. It is not possible to estimate cumulative loading from height change alone. Caregivers who are mostly on their feet should be encouraged to sit during their workday.
12 Future Work

This chapter lists the short term and long term future work that comes out of our findings.

Short term:

- Determine the conditions under which a caregiver can safely perform a patient lift alone, using an overhead lift.
- Study the effect to caregiver workload and gather caregiver feedback on single caregivers performing patient lifting activities alone.
- Test next generation SlingSertor™ prototype with bariatric patients. Evaluate the trade-off between the extra time required to use the device versus the reduced effort. Determine how many lifting sleeves are needed for comfort with various sized patients.
- Expand education campaign for caregivers and the general public to promote a better understanding of the limits of the spine.
- Validate our method for estimating hand forces from ground reactions.

Long term:

- Investigate the relationship between spine shrinkage and inflammation in the spine. Determine if it can be used to differentiate between restorative and damaging cumulative load.
- Use spine shrinkage to clarify if seated workers would benefit from standing breaks or if seated posture is always better for breaks using a seated stadiometer.
References


*Nurses Top for Ethics and Honesty.*


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Appendix A: Calculating Hand Forces and External Moments at the Lumbosacral Joint for the Lift Maneuvering Study

This appendix presents the calculations used to estimate resultant forces and moments in the lift maneuvering study. All calculations assume the coordinate system shown in Figure 54. The method described for calculating resultant forces at the hands relies on the assumption that all movements are performed slowly and therefore dynamic effects are negligible. This accuracy of this assumption could be simply verified by comparing forces measured simultaneously at the hands as well as at the feet.

![Figure 54](image)

Figure 54. The coordinate system used in the lift maneuvering study.

1. **Determine locations of joint centres**

First, the anthropometric measurements (Table 23) and motion capture marker locations (Table 24) were used to calculate the locations of anterior superior iliac spines (RASIS and LASIS). Marker clusters placed at each posterior superior iliac spine (PSIS) landmark (Figure 55) are used to define the location and orientation of the pelvis. Along with markers at LPSIS and
RPSIS, four additional markers were used to estimate pelvic tilt in the saggital plane.

Table 23. Anthropometric measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (N)</td>
<td>BW</td>
</tr>
<tr>
<td>Distance between femoral epicondyles (knee width)</td>
<td>KneeW</td>
</tr>
<tr>
<td>Distance between medial and lateral malleolus (ankle width)</td>
<td>AnkW</td>
</tr>
<tr>
<td>Pubic symphysis height</td>
<td>PSH</td>
</tr>
<tr>
<td>Distance between anterior superior iliac spines (ASIS width)</td>
<td>ASISW</td>
</tr>
<tr>
<td>Height of anterior superior iliac spines (ASIS height)</td>
<td>ASISH</td>
</tr>
<tr>
<td>Distance between posterior superior iliac spines (PSIS width)</td>
<td>PSISW</td>
</tr>
<tr>
<td>Height of anterior superior iliac spines (ASIS height)</td>
<td>ASISH</td>
</tr>
<tr>
<td>Distance between ASIS and PSIS midpoints (pelvis Depth)</td>
<td>PD</td>
</tr>
<tr>
<td>Medial/lateral distance from lateral malleolus to FS4 marker</td>
<td>AnkS</td>
</tr>
<tr>
<td>Anterior/posterior distance from the lateral malleolus to FS6 marker</td>
<td>AnkB</td>
</tr>
<tr>
<td>Height of lateral malleolus above FS4 marker (Ankle height)</td>
<td>AnkH</td>
</tr>
<tr>
<td>Umbilicus height</td>
<td>UH</td>
</tr>
</tbody>
</table>
Table 24. Motion capture markers for lift study

<table>
<thead>
<tr>
<th>Marker Location</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td>ForceShoe markers (Figure 56)</td>
<td>LFS1-6, RFS1-6</td>
</tr>
<tr>
<td>Knee markers (Figure 57)</td>
<td>LK1-3, RK1-3</td>
</tr>
<tr>
<td>PSIS markers (Figure 55)</td>
<td>LPSIS, LPSISA, LPSISb, RPSIS, RPSISA, RPSISb</td>
</tr>
<tr>
<td>T10 marker</td>
<td>T10</td>
</tr>
</tbody>
</table>

Figure 55. PSIS marker locations

Calculate the vector that adds to RPSIS to get RASIS in neutral posture (no pelvic tilt):

\[
\text{RP}_2\text{RA}\_\text{neut} = \text{PT} \times r_{\text{AP}} + \text{(ASISH-PSISH)} \times (0,0,1) + [(\text{ASISW-PSISW})/2] \times r_{\text{RPSIS-LPSIS}}/|\text{RPSIS-LPSIS}|
\]

Where \( r_{\text{AP}} = (r_{\text{RPSIS-LPSIS}} \times (0,0,1))/ |r_{\text{RPSIS-LPSIS}} \times (0,0,1)| \)

Then we perform a transformation that rotates the RASIS coordinate by the amount of pelvic tilt (\(\theta_{\text{ptilt}}\)).

\[
\theta_{\text{ptilt}} = \cos^{-1} \left( (0,0,1) \cdot (r_{\text{RPSISa-RPSISb}})/(|(0,0,1)|^{*} |r_{\text{RPSISa-RPSISb}}|) \right)
\]
$\theta_{\text{pilt0}}$ is the angle of $r_{\text{RPSISa-RPSISb}}$ when the participant is standing in neutral posture.

$$\text{RP\_2\_RA} = \text{RotMat} \ast \text{RP\_2\_RA\_neut}$$

Where $\text{RotMat} =$

$$\begin{bmatrix}
\cos\theta + u_x^2 (1 - \cos\theta) & u_x u_y (1 - \cos\theta) - u_z \sin\theta & u_x u_z (1 - \cos\theta) + u_y \sin\theta \\
 u_x u_y (1 - \cos\theta) + u_z \sin\theta & \cos\theta + u_y^2 (1 - \cos\theta) & u_y u_z (1 - \cos\theta) - u_x \sin\theta \\
 u_x u_z (1 - \cos\theta) - u_y \sin\theta & u_y u_z (1 - \cos\theta) + u_x \sin\theta & \cos\theta + u_z^2 (1 - \cos\theta)
\end{bmatrix}$$

Where $u_x$, $u_y$ and $u_z$ are the components of the normalized rotation axis which is $(\text{RPSIS-LPSIS})$ in this case and

$$\theta = \theta_{\text{pilt}} - \theta_{\text{pilt0}}$$

Therefore,

$$\text{RASIS} = \text{RPSIS} + \text{RP\_2\_RA}$$

Similarly, we find the coordinates of LASIS.

Now find joint centres of the ankles (Lank, Rank), knees (Lknee, Rknee), hips (Lhip, Rhip) as well as the lumbosacral joint (L5S1).

Figure 56 shows where markers were placed on the ForceShoes along with their labels. Each cluster of three markers defines the local coordinate axes for a load cell.

![Figure 56. Right ForceShoe motion capture marker locations RFS1-6. Left ForceShoe markers locations are the mirror image labelled LFS1-6.](image)
Similarly knee marker clusters are shown in (Figure 57). Two markers were placed equidistant from the lateral femoral epicondyle, one above and one below, and a third marker on the midline of the knee joint posterior to the knee, at the same height as the lateral femoral epicondyle when the subject was standing.

Ankle:

The coordinates of the right ankle are found from:

\[
\begin{align*}
RFS_{x} &= \frac{(RFS5-RFS6)}{|RFS5-RFS6|} \\
RFS_{y} &= \frac{(RFS4-RFS5)}{|RFS4-RFS5|} \\
RFS_{z} &= (RFS_{x} \times RFS_{y}) \\
Rank &= RFS5 + AnkB \times RFS_{y} - (AnkS + 0.5 \times AnkW) \times RFS_{x} + AnkH \times RFS_{z}
\end{align*}
\]

Similarly the coordinates of Lank are found.

Hip:

Next the Z coordinate of the pubic symphysis (PS) is found:

\[
PS_{z} = ASIS_{MP}z - ASISH + PSH
\]

Where

\[
ASIS_{MP} = (RASIS+LASIS)/2
\]

(similarly

\[
PSIS_{MP} = (RPSIS+LPSIS)/2
\]

\[
223
\]
The local coordinate system unit vectors for the pelvis are developed:

\[
\begin{align*}
\text{Pelvisx} & = \frac{(\text{RASIS} - \text{LASIS})}{|\text{RASIS} - \text{LASIS}|} \\
\text{Pelvisy} & = \frac{(\text{ASIS}_\text{MP} - \text{PSIS}_\text{MP})}{|\text{ASIS}_\text{MP} - \text{PSIS}_\text{MP}|} \\
\text{Pelvisz} & = (\text{Pelvisx}) \times (\text{Pelvisy})
\end{align*}
\]

Then the right hip joint coordinates are found:

\[
\text{RHip} = \text{RASIS} - 0.79(\text{ASIS}_\text{MPz}-\text{PSz})\text{Pelvisz} - 0.14\text{ASISW}\text{Pelvisy} - 0.34\text{PD}\text{Pelvisx}
\]

Similarly the coordinates of \(L\text{Hip}\) are found.

**Knee:**

\[
\text{Rknee} = \text{RK1} + |\text{RK2-RK1}|\cos(\theta)
\]

Where \(\theta = \cos^{-1}\left(\frac{((\text{RFS5-RFS2})-(\text{RK2-RK1})/(|(\text{RFS5-RFS2})|*|\text{RK2-RK1}|))}{\text{xy}}\right)\) in the xy plane.

Similarly the coordinates of \(L\text{knee}\) are found.

**L5/S1 Joint:**

\[
\text{L5S1} = \text{PSIS}_\text{MP} + 0.34\text{Pelvisy}
\]

2. **Calculate the weight of each segment**

The force of gravity acting on the mass of each segment was then calculated using the values from Table 25 [225, 227].

\[
\begin{align*}
\text{Wp} & = -0.133\text{BW} \\
\text{Wt} & = -0.1455\text{BW} \\
\text{Ws} & = -0.061\text{BW} \\
\text{Wwp} & = -4.22\text{N}
\end{align*}
\]
Table 25. Centre of mass (COM) location with mass of body segments and waist pack

<table>
<thead>
<tr>
<th>Segment</th>
<th>Location of COM</th>
<th>Weight</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>0.612 x distance from umbilicus to midpoint of hip joints</td>
<td>13.30% of BW</td>
<td>COMp, Wp</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.39 x distance from the hip joint to the knee joint</td>
<td>14.55% of BW</td>
<td>COMlt, COMrt, Wt</td>
</tr>
<tr>
<td>Shank and Foot</td>
<td>0.606 x distance from the knee joint centre to the ankle joint centre</td>
<td>6.1% of BW</td>
<td>COMls, COMrs, Ws</td>
</tr>
<tr>
<td>Waist Pack</td>
<td>0.100m inferior and 0.060m posterior to PSIS midpoint</td>
<td>9.81*0.430kg</td>
<td>COMwp, Wwp</td>
</tr>
</tbody>
</table>

3. **Determine the location of the centre of pressures of all four load cells (COPs).**

The six ground reaction forces and moments measured by each of the four load cells in the ForceShoes are shown in Table 26.

Table 26. Forces and moments recorded from the four ForceShoe load cells

<table>
<thead>
<tr>
<th>Load Cell</th>
<th>Short Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ForceShoe, forefoot (RFSF)</td>
<td>FX_RFSF, FY_RFSF, FZ_RFSF, MX_RFSF, MY_RFSF, MZ_RFSF,</td>
</tr>
<tr>
<td>Right ForceShoe, heel (RFSH)</td>
<td>FX_RFSH, FY_RFSH, FZ_RFSH, MX_RFSH, MY_RFSH, MZ_RFSH,</td>
</tr>
<tr>
<td>Left ForceShoe, forefoot (LFSF)</td>
<td>FX_RFSF, FY_RFSF, FZ_RFSF, MX_RFSF, MY_RFSF, MZ_RFSF,</td>
</tr>
<tr>
<td>Left ForceShoe, heel (LFSH)</td>
<td>FX_LFSH, FY_LFSH, FZ_LFSH, MX_LFSH, MY_LFSH, MZ_LFSH,</td>
</tr>
</tbody>
</table>
**Find the global location of the load cells:**

The location of the centre of the right ForceShoe forefoot load cell is found:

\[
\text{RFSF} = \text{RFS1} + (\text{RFS3}-\text{RFS2}) \\
\text{RFSH} = \text{RFS6} + (\text{RFS5}-\text{RFS6})
\]

Similarly, LFSR and LFSH can be found.

For the right ForceShoe forefoot load cell, the local centre of pressure can be found using the following formulas:

\[
\begin{align*}
\text{COPRF}_{x \text{LOC}} &= -[(\text{MY} + \text{Zoff}^*\text{FX})/\text{FZ}] \\
\text{COPRF}_{y \text{LOC}} &= [(\text{MX} - \text{Zoff}^*\text{FY})/\text{FZ}]
\end{align*}
\]

where \( \text{Zoff} = 0 \) m for these load cells. So,

\[
\text{COPRF}_{\text{LOC}} = [\text{COPRF}_{x}, \text{COPRF}_{y}, 0.095]
\]

Similarly, we can find \( \text{COPRH}_{\text{LOC}}, \text{COPLF}_{\text{LOC}} \) and \( \text{COPLH}_{\text{LOC}} \).

**Find the global COP coordinates:**

For the right ForceShoe forefoot load cell:

\[
\text{COPRF} = \text{TransRF}^* \text{COPRF}_{\text{LOC}} + \text{RFSF}
\]

Where

\[
\text{TransRF} = [(\text{RFS2}-\text{RFS1})/|\text{RFS2}-\text{RFS1}|] \\
(\text{RFS2}-\text{RFS3})/|\text{RFS2}-\text{RFS3}|) \\
((\text{RFS2}-\text{RFS1})/|\text{RFS2}-\text{RFS1}|) \times ((\text{RFS2}-\text{RFS3})/|\text{RFS2}-\text{RFS3}|))
\]

Similarly, we can find \( \text{COPRH}, \text{COPLF} \) and \( \text{COPLH} \).

4. **Determine centre of mass (COM) of each segment**

**Right shank:**

\[
\text{COMrs} = \text{Rknee} + 0.606^*r_{\text{Rank-Rknee}}
\]
Similarly, COMIs can be calculated.

**Right thigh:**

\[
\text{COM}_{\text{rt}} = \text{Rhip} + 0.39^\ast \text{r}_{\text{Knee-Rhip}}
\]

Similarly COMlt can be calculated.

**Pelvis:**

First the location of the umbilicus (UM) is found:

\[
\text{UM} = \text{ASIS}_{\text{MP}} + (\text{ASISH-UM})^\ast \text{r}_{\text{T10-PSIS}_{\text{MP}}}
\]

Next the midpoint of the hips is found:

\[
\text{Hip}_{\text{MP}} = (\text{Rhip} + \text{Lhip})/2
\]

\[
\text{COM}_{\text{p}} = \text{UM} + 0.612^\ast \text{r}_{\text{Hip}_{\text{MP}}-\text{UM}}
\]

**Waist Pack:**

\[
\text{COM}_{\text{wp}} = \text{PSIS}_{\text{MP}} - 0.06^\ast \text{Pelvisy} - 0.10^\ast \text{Pelvisz}
\]

5. **Determine the reaction forces at the hands**

Figure 58 shows a free body diagram that demonstrates how hand forces are balanced. First, the hand forces are calculated in the global coordinate system:

\[
\begin{align*}
\text{Fx} &= \text{FX}_{\text{RFSF}} + \text{FX}_{\text{RFSH}} + \text{FX}_{\text{LFSF}} + \text{FX}_{\text{LFSH}} \\
\text{Fy} &= \text{FY}_{\text{RFSF}} + \text{FY}_{\text{RFSH}} + \text{FY}_{\text{LFSF}} + \text{FY}_{\text{LFSH}} \\
\text{Fz} &= \text{FZ}_{\text{RFSF}} + \text{FZ}_{\text{RFSH}} + \text{FZ}_{\text{LFSF}} + \text{FZ}_{\text{LFSH}} - \text{BW}
\end{align*}
\]

These force vectors are then rotated to align with the local coordinate system at the L5S1 joint:

\[
\begin{align*}
\text{Fant}_{\text{pos}} &= \text{RotMat} \ast \text{Fx} \\
\text{Fmed}_{\text{lat}} &= \text{RotMat} \ast \text{Fy} \\
\text{Fvert} &= \text{RotMat} \ast \text{Fz}
\end{align*}
\]
Where RotMat =

\[
\begin{bmatrix}
  r_{\text{ASIS-MP-PSIS-MP}} & r_{\text{ASIS-MP-PSIS-MP}}' \\
  r_{\text{RPSIS-LPSIS}} & r_{\text{RPSIS-LPSIS}}'
\end{bmatrix}
\]

\[= \frac{r_{\text{ASIS-MP-PSIS-MP}}'}{r_{\text{ASIS-MP-PSIS-MP}}} \times \frac{r_{\text{RPSIS-LPSIS}}'}{r_{\text{RPSIS-LPSIS}}} \times \frac{r_{\text{T10-PSIS-MP}}'}{r_{\text{T10-PSIS-MP}}}
\]

and

\[
r_{\text{ASIS-MP-PSIS-MP}}' = r_{\text{RPSIS-LPSIS}} \times r_{\text{T10-PSIS-MP}}
\]

\[
r_{\text{RPSIS-LPSIS}}' = r_{\text{RPSIS-LPSIS}}
\]

\[
r_{\text{T10-PSIS-MP}}' = \text{RotMatTrunk} \times r_{\text{T10-PSIS-MP}}
\]

Where RotMatTrunk =

\[
\begin{bmatrix}
  \cos \theta + u_z^2(1-\cos \theta) & u_xu_y(1-\cos \theta) - u_z\sin \theta & u_xu_z(1-\cos \theta) + u_y\sin \theta \\
  u_xu_y(1-\cos \theta) + u_z\sin \theta & \cos \theta + u_y^2(1-\cos \theta) & u_yu_z(1-\cos \theta) - u_x\sin \theta \\
  u_xu_z(1-\cos \theta) - u_y\sin \theta & u_yu_z(1-\cos \theta) + u_x\sin \theta & \cos \theta + u_x^2(1-\cos \theta)
\end{bmatrix}
\]

Where \( u_x, u_y \) and \( u_z \) are the components of the normalized rotation axis which is \( \text{(RPSIS-LPSIS)} \) in this case and

\[ \theta = \theta_{\text{trunk0}} \]

Where \( \theta_{\text{trunk0}} \) is the angle between the cross product \( \text{(RPSIS-LPSIS)} \times \text{(ASIS_Mp-PSIS_Mp)} \) and \( \text{(T10-PSIS_Mp)} \) in the sagittal plane with the subject standing in neutral posture.
Figure 58. Free body diagram showing how hand forces are balanced by the participant’s body weight and ground reaction forces. Flfsf, Flfsh, Frfsf and Frfsh are the ground reaction forces recorded by the ForceShoes.

6. Determine the moments at the L5/S1 joint in the global reference frame

Figure 58 shows a free body diagram that demonstrates how the moments in the system are balanced. First, moments are summed in the global coordinate system:

\[
\begin{align*}
ML5S1x &= Frfsf^z(COPRFy-L5S1y) + Frfsh^z(COPRHy-L5S1y) \\
&+ Flfsf^z(COPLFY-L5S1y) + Flfsh^z(COPLHy-L5S1y) \\
&+ Wp^z(COMpy-L5S1y) + Wwp^z(COMwpy-L5S1y) \\
&+ Ws^z(COMrsy-L5S1y) + Ws^z(COMlsy-L5S1y) \\
&+ Wt^z(COMrty-L5S1y) + Wt^z(COMlty-L5S1y) \\
&- Frfshy^z(COPRFz-L5S1z) - Frfshy^z(COPRHz-L5S1z) \\
&- Flfshy^z(COPLFz-L5S1z) - Flfshy^z(COPLHz-L5S1z) \\
\end{align*}
\]

\[
\begin{align*}
ML5S1y &= Frfsf^x(COPRFx-L5S1x) - Frfsh^x(COPRHx-L5S1x) \\
&- Flfsf^x(COPLFx-L5S1x) - Flfsh^x(COPLHx-L5S1x) \\
\end{align*}
\]
- $W_p^*(COM_{px}-L5S1x) - W_{wp}^*(COM_{wp}-L5S1x)$
- $W_s^*(COM_{rsx}-L5S1x) - W_s^*(COM_{lsx}-L5S1x)$
- $W_t^*(COM_{rtx}-L5S1x) - W_t^*(COM_{ltx}-L5S1x)$
- $Fr_{fsfx}^*(COPR_{Fz}-L5S1z) + Fr_{fshx}^*(COPR_{Hz}-L5S1z)$
- $Fl_{fsfx}^*(COP_{LFz}-L5S1z) + Fl_{fshx}^*(COP_{LHz}-L5S1z)$

$$ML_{5S1} = Fr_{fsfy}^*(COPR_{Fx}-L5S1x) + Fr_{fshy}^*(COPR_{Hx}-L5S1x)$$
$$+ Fl_{fsfy}^*(COPL_{Fx}-L5S1x) + Fl_{fshy}^*(COPL_{Hx}-L5S1x)$$
$$- Fr_{fsfx}^*(COPR_{Fy}-L5S1y) - Fr_{fshx}^*(COPR_{Hy}-L5S1y)$$
$$- Fl_{fsfx}^*(COPL_{Fy}-L5S1y) - Fl_{fshx}^*(COPL_{Hy}-L5S1y)$$

And

$$ML_{5S1} = [ML_{5S1x}, ML_{5S1y}, ML_{5S1z}]$$

Figure 59. Free body diagram showing how moments are balanced at the L5/S1 joint. $Fl_{fsi}$, $Fl_{fsh}$, $Fr_{fsf}$ and $Fr_{fsh}$ are the ground reaction forces recorded by the ForceShoes.
7. Rotate moments to match the local coordinate system at the L5/S1 joint

\[ \text{ML5S1Local} = \text{RotMat} \times \text{ML5S1} \]

Where \( \text{ML5S1Local} = [\text{Msb}, \text{Mfb}, \text{Mtw}] \)
Appendix B: Calculations for Estimating Resultant Forces and Moments for the Sling Insertion Study

This appendix describes how resultant forces and moments were calculated in the sling insertion study. All calculations assume the coordinate system shown in Figure 60. As in Appendix A, the method described for calculating resultant forces at the hands relies on the assumption that all movements are performed slowly and therefore dynamic effects are negligible. This accuracy of this assumption could be simply verified by comparing forces measured simultaneously at the hands as well as at the feet.

Figure 60. The coordinate system used in the sling insertion study.

1. **Determine locations of joint centres**

Joint centre calculations are the same as in Appendix A with a few changes due to differences in motion capture markers on the feet. Markers were placed at the lateral malleolus, calcaneus and fifth metatarsal head. Short form labels for these markers are given in Table 27.
Table 27. Motion capture markers for sling study

<table>
<thead>
<tr>
<th>Marker Location</th>
<th>Labels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot markers</td>
<td>RM5, RLM, RCAL, LM5, LLM, LCAL,</td>
</tr>
<tr>
<td>Knee markers (Figure 57)</td>
<td>LK1-3, RK1-3</td>
</tr>
<tr>
<td>PSIS markers (Figure 55)</td>
<td>LPSIS, LPSISa, LPSISb, RPSIS, RPSISa, RPSISb</td>
</tr>
<tr>
<td>T10 marker</td>
<td>T10</td>
</tr>
</tbody>
</table>

**Ankle:**

The coordinates of the right ankle are found from:

\[
\text{Rank} = \text{RLM} + 0.5 \times \text{AnkW} \times ((0,0,1) \times (\text{RM5}-\text{RLM}))
\]

Similarly the coordinates of Lank are found.

**Knee:**

\[
\text{Rknee} = \text{RK1} + |\text{RK2-RK1}| \times \cos(\theta)
\]

Where \( \theta = \cos^{-1} \left( \frac{(\text{RLM-RM5}) \cdot (\text{RK2-RK1})}{(|(\text{RLM-RM5})||\text{RK2-RK1})|} \right) \) in the xy plane.

Similarly the coordinates of Lknee are found.

2. **Calculate the weight of each segment**

Segment weights are found as in Appendix A.

3. **Determine the location of the COPs of the two lean-bar load cells and the two forceplates**

The six ground reaction forces and moments measured by each of the four load cells in the ForceShoes are shown in Table 26.
Table 28. Forces and moments recorded from the two lean bar load cells and the two force plates

<table>
<thead>
<tr>
<th>Load Cell</th>
<th>Short Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right force plate (RFP)</td>
<td>FX_RFP, FY_RFP, FZ_RFP, MX_RFP, MY_RFP, MZ_RFP,</td>
</tr>
<tr>
<td>Left force plate (LFP)</td>
<td>FX_LFP, FY_LFP, FZ_LFP, MX_LFP, MY_LFP, MZ_LFP,</td>
</tr>
<tr>
<td>Right lean-bar load cell (RLB)</td>
<td>FX_RLB, FY_RLB, FZ_RLB, MX_RLB, MY_RLB, MZ_RLB,</td>
</tr>
<tr>
<td>Left lean-bar load cell (LLB)</td>
<td>FX_LLB, FY_LLB, FZ_LLB, MX_LLB, MY_LLB, MZ_LLB,</td>
</tr>
</tbody>
</table>

**Find the global location of the load cells:**

The location of the centre of the load cells and forceplates are found as RLB, LLB, RFP and RFP using motion capture markers attached to each device.

The COP for each device is found using the same formulas shown in Appendix A:

\[
\begin{align*}
\text{COP}_{x\text{LOC}} &= -((\text{MY} + \text{Zoff} \times \text{FX}) / \text{FZ}) \\
\text{COP}_{y\text{LOC}} &= ((\text{MX} - \text{Zoff} \times \text{FY}) / \text{FZ})
\end{align*}
\]

where Zoff = -0.001428m for the right forceplate, -0.001388m for the left forceplate and -0.001634 for both lean-bar load cells. This gives us these four local COPs: COPRLB_LOC, COPLLB_LOC, COPRFP_LOC and COPLFP_LOC.

**Find the global COP coordinates:**

The local COPs are rotated and translated to their global positions as in Appendix A to find: COPRLB, COPLLB, COPRFP and COPLFP.
4. **Determine COMs of each segment**

Segment COMs are found as in Appendix A.

5. **Determine the reaction forces at the hands**

Figure 61 shows a free body diagram that demonstrates how hand forces are balanced. First, the hand forces are calculated in the global coordinate system:

\[
\begin{align*}
F_x &= FX_{RLB} + FX_{LLB} + FX_{RFP} + FX_{LFP} \\
F_y &= FY_{RLB} + FY_{LLB} + FY_{RFP} + FY_{LFP} \\
F_z &= FZ_{RLB} + FZ_{LLB} + FZ_{RFP} + FZ_{LFP} - BW
\end{align*}
\]

These force vectors are then rotated to align with the local coordinate reference frame at the L5S1 joint as in Appendix A.

\[
\begin{align*}
F_{med\_lat} &= RotMat \times F_x \\
F_{ant\_pos} &= RotMat \times F_y \\
F_{vert} &= RotMat \times F_z
\end{align*}
\]
Figure 61. Free body diagram showing how hand forces are balanced by the participant’s body weight, ground reaction forces and lean bar forces. Fllb and Frlb are the forces recorded by the lean-bar. Flfp and Frfp are the forces recorded by the forceplates.

6. **Determine the forces and moments at the L5/S1 joint in the global reference frame**

Figure 62 shows a free body diagram that demonstrates how the forces and moments in the system are balanced. First, forces and moments are summed in the global coordinate system:

\[
\begin{align*}
FL5S1x &= FX_{RLB} + FX_{LLB} + FX_{RF} + FX_{LFP} \\
FL5S1y &= FY_{RLB} + FY_{LLB} + FY_{RFP} + FY_{LFP} \\
FL5S1z &= FZ_{RLB} + FZ_{LLB} + FZ_{RFP} + FZ_{LFP} - 2(Ws + Wt) - Wp
\end{align*}
\]
ML5S1x = FRLBz*(COPRLby-L5S1y) + FLLBz*(COPLLBy-L5S1y) + FRFPz*(COPRFPy-L5S1y) + FLLBPz*(COPLFPy-L5S1y) + Wp*(COMpy-L5S1y) + Ws*(COMry-L5S1y) + Wt*(COMty-L5S1y) - FRLBy*(COPRLBz-L5S1z) - FLLBy*(COPLLBz-L5S1z) - FRFPy*(COPRFPz-L5S1z) - FLFPy*(COPLFPz-L5S1z)

ML5S1y = FRLBx*(COPRLBx-L5S1x) + FLLBx*(COPLLBx-L5S1x) - FRFPx*(COPRFPx-L5S1x) - FLLBPx*(COPLFPx-L5S1x) - Wp*(COMpx-L5S1x) - Ws*(COMmsx-L5S1x) - Wt*(COMtrty-L5S1y) - FRLBx*(COPRLBz-L5S1z) + FLLBx*(COPLLBz-L5S1z) + FRFPx*(COPRFPz-L5S1z) + FLFPx*(COPLFPz-L5S1z)

ML5S1z = FRLBy*(COPRFX-L5S1x) + FLLBy*(COPHx-L5S1x) + FRFPy*(COPLFy-L5S1y) + FLFPx*(COPHFy-L5S1y) - FRLBx*(COPRFy-L5S1x) - FLLBx*(COPHY-L5S1y) - FRFPx*(COPLFHy-L5S1y) - FLFPy*(COPHFLy-L5S1y)

Therefore

FL5S = [FL5S1x, FL5S1y, FL5S1z]
ML5S = [ML5S1x, ML5S1y, ML5S1z]
Figure 62. Free body diagram showing how ground and bedside reaction forces and moments are balanced at the L5/S1 joint. Flb and Frlb are the forces recorded by the lean-bar. Flfp and Frfp are the forces recorded by the forceplates.

7. **Rotate moments to match the local coordinate system at the L5/S1 joint.**

\[
FL5S1\text{Local} = \text{RotMat} \times FL5S1 \\
ML5S1\text{Local} = \text{RotMat} \times ML5S1
\]

Where RotMat =

\[
\begin{bmatrix}
    r_{\text{ASIS-MP}} \times r_{\text{PSIS-MP}}' \\
    r_{\text{RPSIS-LPSIS}}' \\
    r_{\text{T10-Psis-MP}}' \\
\end{bmatrix}
\]

and

\[
r_{\text{ASIS-MP}} \times r_{\text{PSIS-MP}}' = r_{\text{RPSIS-LPSIS}}' \times r_{\text{T10-Psis-MP}}'
\]
\[ r_{\text{RPSIS-LPSIS}} = r_{\text{LPSIS}} \]

\[ r_{T10-\text{PSIS}_\text{MP}} = \text{RotMatTrunk} \cdot r_{T10-\text{PSIS}_\text{MP}} \]

Where RotMatTrunk =

\[
\begin{bmatrix}
\cos\theta + u_x^2(1-\cos\theta) & u_xu_y(1-\cos\theta) - u_y\sin\theta & u_xu_z(1-\cos\theta) + u_z\sin\theta \\
u_xu_y(1-\cos\theta) + u_y\sin\theta & \cos\theta + u_y^2(1-\cos\theta) & u_yu_z(1-\cos\theta) - u_z\sin\theta \\
u_xu_z(1-\cos\theta) - u_z\sin\theta & u_xu_y(1-\cos\theta) + u_y\sin\theta & \cos\theta + u_z^2(1-\cos\theta)
\end{bmatrix}
\]

Where \( u_x \), \( u_y \) and \( u_z \) are the components of the normalized rotation axis which is \( \text{RPSIS-LPSIS} \) in this case and

\[ \theta = \theta_{\text{trunk0}} \]

Where \( \theta_{\text{trunk0}} \) is the angle between the cross product \( (\text{RPSIS-LPSIS}) \times (\text{ASIS}_\text{MP}-\text{PSIS}_\text{MP}) \) and \( (T10-\text{PSIS}_\text{MP}) \) in the sagittal plane with the subject standing in neutral posture.

and

\[ \text{FL}5\text{S1Local} = [Fx, Fy, Fz] \]
\[ \text{ML}5\text{S1Local} = [Mx, My, Mz] \]

8. **Determine the local loads at the L5/S1 joint**

Finally, we estimate internal spine compression at L5/S1 using single equivalent muscle model:

\[ F_{\text{fb}} = \text{abs}(\text{ML}5\text{S1Local}_x/r_{\text{fb}}) \]
\[ F_{\text{ssb}} = \text{abs}(\text{ML}5\text{S1Local}_y/r_{\text{ssb}}) \]
\[ F_{\text{twt}} = \text{abs}(\text{ML}5\text{S1Local}_z/r_{\text{twt}}) \]

where \( r_{\text{fb}} \), \( r_{\text{ssb}} \) and \( r_{\text{twt}} \) are the moment arms given in Table 20. Note that \( r_{\text{fb}} \) changes depending on whether the trunk is in flexion or extension.

\[ F_{\text{compL5S1}} = \text{FL}5\text{S1LOC}_y + F_{\text{fb}} + F_{\text{ssb}} + F_{\text{twt}} \]
Appendix C: Foot-Shank Single Segment Assumption

In this appendix, we consider the error in treating the foot and shank as a single segment. We calculate the error between these two cases:

a) The foot and shank are treated as a single segment weighing 6.1% BW with COM located 60.6% of the distance from the knee to the ankle.

b) The foot and shank are two segments weighing 1.45% and 4.65% of body mass, respectively. The COM of the foot is taken to be half way between the lateral malleolus and the head of metatarsal II. The COM of the leg is 43.3% of the distance from the knee to the ankle.

These two cases are illustrated in Figure 63.

Figure 63. a) The foot and shank are treated as a single segment b) The foot and shank are treated as separate segments

We reanalysed the data from the 10 trials shown in Table 29 modelling the foot and shank as separate segments and found an RMS errors of 0.27Nm in the forward bending and 0.66Nm in the side bending external moments. Since these errors are an order of magnitude smaller than the standard deviation in our mean peak moment estimates (~10Nm), we can safely assume these errors are negligible.
Table 29. Trials used to calculate error in treating foot and shank as a single segment

<table>
<thead>
<tr>
<th>Study</th>
<th>Trial Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift maneuvering</td>
<td>S2, Solo, Floor, Push</td>
</tr>
<tr>
<td>Lift maneuvering</td>
<td>S5, Sec, Overhead, Pull</td>
</tr>
<tr>
<td>Lift maneuvering</td>
<td>S10, Pri, Floor, Turn</td>
</tr>
<tr>
<td>Lift maneuvering</td>
<td>S16, Sec, Overhead, Legs Down</td>
</tr>
<tr>
<td>Lift maneuvering</td>
<td>S20, Solo, Floor, Legs Up</td>
</tr>
<tr>
<td>Sling insertion</td>
<td>S3, Solo, Roll Right</td>
</tr>
<tr>
<td>Sling insertion</td>
<td>S5, Right, Roll Back</td>
</tr>
<tr>
<td>Sling insertion</td>
<td>S8, Left, Connect Sling</td>
</tr>
<tr>
<td>Sling insertion</td>
<td>S11, Solo, Leg Strap</td>
</tr>
<tr>
<td>Sling insertion</td>
<td>S15, Right, Roll Left</td>
</tr>
</tbody>
</table>
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