Ergonomic Assessment of a Robotic Assisted Transfer Device to Perform Caregiver Assisted Wheelchair Transfers

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Depending on the nature of an injury or illness, a care recipient benefits from caregiver assistance when moving to and from a target surface, a maneuver known as an assisted transfer. When performed manually, that is physically with no assistance, a transfer exposes the caregiver to muscle fatigue in the back, shoulders, and upper extremities, endangering themselves as well as their care recipient. Because of the relief they provide caregivers, transfer lift systems are becoming a common clinical standard to counter exposure to such risk factors. Use of such devices improves the safety of performing transfers as well as their efficiency. As the population continues to age and society becomes more inclusive of disability, it is imperative to advance such technologies as to improve their usability in and out of a clinical workspace. Robotics present a unique opportunity for caregivers to perform a safe and effective transfer while reducing the risk for musculoskeletal injury and progressing independent living for a mobility device user. The purpose of this project was to assess caregivers performing transfers using a portable, ambidextrous robotic assisted transfer device (RATD). This was performed over the course of two studies: (1) a "proof of concept" assessment in which the trunk kinematics and usability feedback from caregivers (N=21) were compared between a prototype of the novel RATD and a Mechanical Floor Lift (the clinical standard of care), and (2) an ergonomic assessment in which caregivers (N=28) conducted transfers on their paired care recipient (N=28) using a second generation RATD, from which trunk kinematics, usability feedback, cognitive load, and muscle activation was compared to the Mechanical Floor Lift. The outcomes of both studies provided insight and promise into the application of a novel engineering concept to advance performance of a critical activity of daily living (ADL) for people living with a mobility impairment as well as to improve quality of care delivery provided by their caregivers.

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Preface

Strong Arm's assessment was possible because of the hard work and dedication of countless faculty, staff members, and students. Thank you to my advisor, Dr. Rory Cooper for his unwavering encouragement, mentorship, and motivation to assist those with disabilities through novel advancements in assistive technology. Additionally, thank you to Dr. Alicia Koontz and Dr. Roxanna Bendixen for their teachings and willingness to assist me in mastering the appropriate material in and out of this project. Rosemarie Cooper and COL Matt St. Laurent provided unique services to assist with understanding the clinician perspective and for that I am also grateful for their respective contributions. Thank you to engineers, Josh Brown, Ben Gowarski, and Matt Landis for assisting me whenever Strong Arm needed repairs or upgrades. Thank you to Theresa Crytzer for providing me the training to properly interact with caregivers and provide a safe and effective method to transfer mobility device user participants. Thank you to Nikitha Deepak and Stacy Eckstein for ensuring the safety of not only our research participants but myself as well during subject testing. Thank you to my interns, Sara Hackett, Nick Gatto, and Jordan Hoydick for assisting with data collection and hope they found the experience to be useful. Thank you to Eline Blaauw, Dr. Sarah Bass, and Hailee Kulich for their patience and support for me to master biomechanics and the related outcomes of this project. Finally, thank you to Mom, Dad, Andrew, Abigail, the rest of my family, and my friends for their love and support throughout my dissertation process. Without any of these people, this project would not have been possible.

1.0 Introduction

The following section gives an overview of why this project was conducted, the importance of its outcomes, and the objectives used to guide the two studies.

1.1 Project Purpose

Approximately 3.6 million Americans require mobility based assistive technologies (i.e power/manual wheelchairs, scooters, etc.) to perform activities of daily living (ADLs) crucial to ambulation [1,2]. A mobility device user conducts a transfer, an example of one such ADL, to and from their assistive devices for purposes that include using the restroom, participating in clinical exercises, or taking a shower/bath. If performed incorrectly or with minimal training, the transfer is dangerous and anxiety provoking, which reduces a mobility device user's ability to participate in other ADLs [3-5]. Assistance provided by a caregiver may be warranted depending on the nature of the individual's disability, because it improves confidence and self-efficacy for a mobility device user to participate in society [6, 7].

Musculoskeletal injury is a growing public health concern in the healthcare industry, especially with a growing geriatric population [7-10]. Caregivers, both formal (i.e. nurses and occupational therapists) and informal (i.e family members), report muscle related strain and occupational fatigue as a result of transfer induced motion in the back and shoulders [11-13]. The problem becomes exacerbated when accompanied with obese care recipients, while working prolonged work shifts, lower staff turnover, increased hospital visits, and higher client load [12, 13]. As a result, caregivers risk developing a long-term disability of their own, which reduces quality of care delivery and quality of life for caregivers and care recipients [14, 15].

For caregivers in the United States, Transfer Lifts reduce the load bearing associated with a care recipient's weight, while also improving navigation towards a target surface (i.e a toilet) [2, 7, 12, 16-18, 24-29]. This technology exists in different iterations, most notably floor and ceiling lifts [2, 7, 20-22]. Current standards of care are engineered through multiple systems, appealing to caregivers who take advantage of them, and thought to be responsible for reduced work-related injuries [9, 10, 21-23]. Though transfer devices reduce the necessity of manually transferring a care recipient, their design, size, and systems create difficulties preventing efficient and safe utilization [2, 7, 21-24]. For instance, floor lifts still require repetitive maneuvering in the caregiver's back, while immobile ceiling lifts are not applicable to various non-clinical spaces [2, 7].

The ergonomic shortcomings of transfers and transfer device systems indicate an opportunity to advance the convenience and safety of these devices in order to increase confidence for a caregiver and mobility device user [2, 6, 7, 30]. Not only would a portable powered assisted device with a feasible machine interface system reduce the physical demand of transfer on a caregiver, but theoretically, a mobility device user could obtain the ability to transfer themselves [7, 30-33]. In a recent consumer poll on assistive technology research, caregivers and mobility device users stressed the importance of advancements in transfer lift technologies [2, 23, 30]. This participatory design and research approach provide investigators with a roadmap to develop a technology that would provide a usable human-machine interface to an end user as well as an applicable machine to conduct the transfer and a consumer would potentially be willing to use [2, 30, 32].

A robotic assisted transfer device (RATD) represents an opportunity to alleviate the barriers caregivers and care recipients face during a transfer by providing advancements compared to current standards of care [2, 7, 23, 30-32]. RATDs exist in multiple iterations. For example, Strong Arm, addresses the desire for a transfer system that is easy to manipulate and control, is usable in non-clinical environments, and requires little to no caregiver strain [7, 33]. Additional independence and reduced discomfort are possible with this technology in both caregivers and their care recipients during the transfer process [30-33]. RATDs are an enticing advancement but, before this research, lacked research on clinical usability, feasibility, and effectiveness outcomes.

1.2 Study Importance and Field Impact

The following project was a comprehensive ergonomic assessment of an RATD, because of the clinical outcomes provided from a sample of caregivers using an RATD to conduct assisted transfers. Feedback on cognitive load, muscle activation, trunk range of motion, and linear kinematics of the pelvis and compared to a clinical standard. Information gathered presented a unique opportunity to introduce a novel concept that in theory, could be utilized in and out of the clinical space. For starters, this study provided rehabilitation sciences insight into the application of robotics with assistive technology, specifically for the purposes of preventing injury and improving quality of life in both caregivers and mobility device users involved in the transfer process. Additionally, the research provided feedback to better understand the kinematics and muscle activation occurring during caregiver assisted transfers, which sets the framework for future work with such technology. Psychology and social sciences are provided with information about personal appeal towards the application of novel technology to rehabilitation in addition to cognitive load experienced using a transfer lift. Overall, the confirmation of this RATD, the Strong Arm, as a usable assisted transfer increased evidence for its eventual introduction into the healthcare market.

1.3 Study Objectives

The overarching objective driving this research compared the ergonomics of a novel rehabilitation engineering concept, the RATD, to the clinical standard of care, to reduce risks for occupational injury and fatigue and to improve quality of care delivery provided by formal and informal caregivers. Specifically, investigators were interested in assessing the following outcomes: device usability, cognitive load, back, shoulder, and upper extremity muscle electromyography, range of trunk flexion-extension, lateral bend, and axial rotation, and pelvis distance traveled, transfer time, pelvis velocity, and pelvis acceleration. Objectives are outlined below.

- Objective 1: Assess the ergonomics and biomechanics in caregivers using a novel robotic assisted transfer device to conduct dependent wheelchair transfers

- Objective 2: Compare the transfer usability, demand, times, and trunk movements of dependent wheelchair transfers conducted of a prototype of a robotic assisted transfer device and compare outcomes with the clinical standard of care

- Objective 3: Conduct a pilot study comparing the ergonomics of an updated version of the robotic assisted transfer device with the standard of care

2.0 Literature Review

This chapter details a review of the literature and scientific insight on topics important to successful completion of this project. An overview of the importance of a transfer are discussed, in addition to the facilitators and barriers of a caregiver assisted transfer. Various assisted transfer devices are introduced as well as select operating systems. Finally, the preliminary research and development of the Strong Arm RATD concept is outlined.

2.1 Transfers and Independent Living for Mobility Device Users

Transfers are significant to the successful completion of ADLs related to rehabilitation, social interactions, and independent living. Such maneuvers are difficult to perform and the strain they place on a mobility device user increase risk of social isolation [2-7]. Because accidents exacerbate an existing disability, transfers are dangerous if performed inappropriately [3-5]. Wheelchair users are at risk for shoulder pain as well as falls during transfers, which are responsible for 64-80% of wheelchair related emergency room visits [3-5]. Such incidents further increase performance anxiety around such a maneuver and only hinder the efforts to improve community integration and participation in society [3-6]. This also exacerbates the threat of social isolation, which heightens additional emotional distress and reduced quality of life [2, 6].

2.2 Caregiver Assisted Transfers

Caregivers are essential to the well-being and independent living of select mobility device users by alleviating concerns and difficulties pertaining to the transfer process [2, 6, 7, 23, 33]. This section introduces the facilitators and barriers both caregivers and their care recipients may face during a transfer, the epidemiology behind work related injury in healthcare, the basic biomechanics of a transfer, and the impact of assisted transfer injury on quality of life.

2.2.1 Facilitators and Barriers

Caregiver assistance enhances a wheelchair user's activity and participation in society by providing access to other inaccessible environments [6]. When manually assisted by a caregiver (manual referring to transferred without technological assistance), a care recipient requires less exertion to get in and out of a chair, providing them with a sense of comfort and stability [2, 6, 33]. This reduces the risk related to prolonged sedentary activity, such as pressure ulcers [6, 7, 18-20]. In assisting activities, such as the transfer, caregivers also increase self-efficacy, and therefore confidence, to complete essential activities of daily living (ADLs) [6, 33].

Several barriers impede success of a caregiver assisted transfer. Because most transfers are time consuming and require more than one caregiver present, another care recipient, for instance a hospital patient, may be left unattended for prolonged periods of time, increasing the risk for pressure ulcers [1,2,7,21,34]. Accidents are also prevalent, with 8.1% of wheelchair accidents relating to caregiver actions, including poor patient handling [4, 10]. Much like independent transfers, if performed inappropriately, assisted transfers prove to be dangerous if not fatal [5, 10, 15]. For instance, a care recipient may tear a rotator cuff, which potentially leads to internal bleeding, and risks being dropped, which is problematic among those on blood thinners [15, 18-22]. Privacy concerns create an additional psychological barrier. Care recipients lose a sense of dignity during activities such as using the bathroom, which hinders the relationship between the caregiver and the care recipient [5,6,33]. As a result, both caregivers and those with mobility impairments risk developing further disabilities resulting from poor mental health [19].

2.2.2 Transfer Kinematics and Muscle Activation

According standards developed by the National Institute of Occupational Safety and Health (NIOSH), a healthcare worker should not lift more than 3400 N during a typical eight hour shift [17]. This matches similar guidelines set by the International Observational Society (ISO), which recommend no more than 10 kg per lift [16]. Despite these guidelines, certain work-related activities require well over this limit, creating physical strain and fatigue which short- and long-term repercussions [35-42]. Ergonomics and clinical biomechanics literature suggest caregivers are exposed to prolonged periods of awkward posturing because of the frequency and intensity of load bearing. When conducting a transfer, a caregiver spends about 25% of their time flexing their trunk greater than 30 degrees [34, 35]. Additionally, twisting and stretching of the waist increases lateral bend and axial rotation joint angles and range of motion.

Such motions are implicated in 50% of caregivers as a cause of the discomfort experienced from occupational activities, which is potentially worse in informal caregivers who do not receive appropriate clinical training [37, 43]. Heavy load bearing from transfers puts strain on various muscles along the trunk, particularly the lumbar-paraspinal region [44-46]. Repetitive flexion and rotation breaks down muscles in the back, which generally act as a defense mechanism to dangerous sheer and compression that act on the L5/S1 center of mass [36, 38-47]. However, it's the repetitive, prolonged nature of the transfer, particularly when done repeatedly, that likely exacerbates muscle degradation and failure [36]. The greater the external force, the greater the strain on the low back, which risks breakdown and pain as a result, thus increasing the burden facing caregivers [44-48].

2.2.3 Epidemiology of Work-Related Musculoskeletal Pain in Caregivers

Disorientation of the fibers in the back muscles reduces their ability to protect against overexertion, which leaves caregivers vulnerable to musculoskeletal pain and fatigue [25, 45, 49]. According the United States Bureau of Labor Statistics, healthcare is the most at-risk occupation for non-fatal injury with 6 out of 100 healthcare workers reporting injury or at least once in 2016, including 60,000 cases of musculoskeletal injury [9, 10]. Overexertion and body misalignment are cited as the cause of 46-69% of injuries reported from 67 out of 10,000 nurses as 107 out of 10,000 homecare aids, and 174 out of 10,000 emergency medical technicians perform overexertion activities as part of their profession [11-14]. This, in addition to lifting a cumulative 1.8 tons during a typical shift, explains the high prevalence of musculoskeletal injury reported in caregivers, both formal (i.e Occupational Therapists, Nurses, etc.) and informal (Family, Friends, etc.), which ranges from 74 to 98% [13].

Though pain is reported throughout the body, 49-62% of the pain is reported in the lower back [11-14, 35-37]. For any given year, approximately 50% of nurses report low back pain while 80% report a low back pain at least once in their careers [38-42]. In the population of professionals who spend the most amount of time with care recipients, that is nurses and nursing assistants, the risk for low back pain is 3.2 and 7 times higher compared to the average respectively, an outcome that is affected by the number of transfers, repetitive nature of their work, and low bed to staff ratios [13, 34-36]. Informal caregivers are not provided with the same resources as someone with inpatient clinical expertise and therefore are more likely to perform transfers that are biomechanically inappropriate [8, 33, 37-39]. Low back pain has a negative impact on the US economy as it is responsible for 1400 workers compensation claims per 10,000 equivalents and 50,000 days away from work [34-36]. This represents a $2 billion impact on the economy, a burden that is higher when incorporating the $14 billion burden from informal caregiver injury [14].

2.2.4 Impact on Care Delivery and Health Related Quality of Life

Transfer, and patient handling, related pain and fatigue is potentially long-lasting for both the caregiver and the care recipient. [13]. Across different hospitals, healthcare workers report task failure when asked about the physical demand and effort exerted into occupational activities [50]. Ignoring pain for fear of judgment or underestimating its severity reduces the chance a caregiver takes a day off or files a claim and therefore, reduces occupational performance [13, 50]. Nurses report an 80% burnout rate and 51% high burden of care which influence considerations for a career change [13]. Self-confidence and reduced professional performance are areas to address as they lead to additional physical and emotional distress if left unchecked [3,39].

Caregiver pain and fatigue, if left unchecked, worsens into chronic health conditions [37, 45, 46]. Sleep disturbances are common in those who provide more than five hours of caregiver related services per day while 34 out of 1000 healthcare workplace events are due to a lack of sleep [49]. Acute low back pain risks becoming chronic and becoming itself, a disability [49]. Caregivers also tend to suppress frustration, sadness, and stress, report impairing substance abuse, and rates of depression and anxiety that correlate to high physical strain [6, 8, 48, 49]. Such mental health issues, reported in 46% of nurses, exacerbate pain and comorbid health issues and particularly problematic in caregivers with recipients underestimating their burden [3, 48-50]. As a result, 1.37 out of 1000 caregivers' risk permanent disability themselves as a result of their low back pain and the ensuing issues [8, 36, 42].

2.3 Assisted Transfers Lifts Facilitators and Barriers

Because of the risks performing transfers manually impose on a caregiver and care recipient, several states and hospital systems have implemented "no manual lift" policies. In other words, no lifting should be done without assistance of another caregiver or transfer related intervention. This suggests a promotion of safer methodologies and equipment to assist with transferring and heavy lifting activities [2, 7, 23, 25-29, 33]. Transfer Lifts were introduced to circumvent the work-related injuries while also providing a safer and more efficient method of transfer delivery services. Current clinical standards of care involve usability and effectiveness of mechanical and electrical transfer devices.

Figure 1 Example of a Floor Lift with a Mechanical Operating System and a Ceiling Lift with an Electronic Based System [33]

2.3.1 Transfer Lift Iterations and Systems

There are three aspects that contribute towards this: administrative, engineering and work practice controls [7, 23, 33]. Administrative controls refer to management-based policies and regulations that may reduce exposure of injury to both caregivers and care recipients [33]. Work practice controls involve caregiver training to perform transfers correctly [33]. Engineering controls include transfer devices preventing work-related musculoskeletal hazards.

Floor lifts and ceiling lifts are two commonly cited assisted transfer technologies [7, 25-29, 51, 52]. Floor lifts, such as the Hoyer Advance, are sling and harness-based devices in which a caregiver can wheel a patient or a loved one over longer distance to a target destination. By carrying a bulk of the care recipient's weight, a floor lift reduces the load placed on a caregiver, reducing the amount when transferring manually [2, 7, 23, 25-29, 43]. From a biomechanics perspective, caregivers using a floor lift, compared to manual lifting, significantly lowered erector spinae muscle activation and trunk flexion, because of the reduced exposure to sheer and compression acting on the L5/S1 center of mass [24, 25]. However, compared to automated ceiling lifts, caregivers prefer the automation and smoother transfers such devices have to offer to the transfer [24]. Ceiling lifts, also known as overhead lifts, rotate along a track attached to a ceiling, or another foundation, in setting that include but are not limited to a clinic, toilet, or bathtub [7, 19, 24, 33]. By strapping a care recipient into a sling or chair, a care recipient potentially requires little interaction from a caregiver and may even can transfer themselves.

Floor and ceiling assisted devices are operated by several systems though mechanical and electrical are most common [2, 7, 33, 51, 52]. Mechanical lift systems utilize compression as its primary source of power [43-45]. A handle is turned in order to trap air while a user pumps a lever to lift a care recipient via a harness and sling system [7, 33]. The user then turns the handle in order to release air when placing the recipient at their desired destination [7, 33]. Such a system is easy to understand and implement for a transfer. [7, 33]. When using an electronic operating system, caregivers rely on an external machine interface powered by various electrical circuits, motors, and actuators [7, 25]. By relying on a device that requires little to no strain to perform a transfer, the caregiver potentially reduces a risk for injuring themselves or someone else, while relieving personal fatigue over a long period of time [51, 52]. Such a system is confirmed in the biomechanics and ergonomics literature [25-29]. When compared with one another, caregivers and care recipients both preferred ceiling lifts to floor lifts, because they require little strain for a transfer [24]. Compared to mechanical floor lifts, those that were motor powered required a lower operating force to push and pull force at the initiation of a transfer [29].

Assessments of floor lifts report significantly reduced musculoskeletal strain in the form of reduced muscle activation, self-reported feedback, and reduced days off due to injury or illness in the healthcare professions [51]. The odds of low back pain in healthcare centers with Transfer Lifts were 41% lower than those without Transfer Lifts [53]. This also financially awards the delivery setting as those with more lifts offered as part of re-education programs were responsible for a reduced risk for low back pain in the clinical space, indicating the potential of lift systems to replace manual techniques in the healthcare setting [52]. A study on workers compensation claims in a hospital setting that recently implemented lift systems found a reduction in claims from 10.3 per 100 workers to 3.8 per 100 workers [54].

Though transfer lifts are more desirable than manual transferring, they consist of several ergonomic shortcomings that require attention. A mechanical lift requires personal maneuvering to transfer a care recipient and is a two-person job, indicating a potential for a healthcare worker to abandon their position caring for another patient [7, 33, 49]. Additionally, assisted device find their accessibility to be limited to a clinic or home, thus limiting their ability for use outside of these settings [4, 5]. Because of the short supply and their complexity, caregivers resort back to manual transferring [2,4,5,7,14]. Additionally, significantly more variability in transfer times is reported during mechanical lift transfers compared to those conducted with more efficient systems, indicating some transfers might be rushed while other may take extensive periods of time [56].

This problem extends to informal caregivers as well, who may not prepare properly for performance of such activities, which potentially increases risk for accidents from improper use [3-7]. As such, previous literature may not consider, the burden one may face using current assisted devices [7, 33, 49]. For instance, a previous study assessing low back electromyography found approximately 30% average muscle activation in the erector spinae during both lifting and placement exercises, which may indicate a steady degree of strain when transferring a care recipient [4, 40]. Assisted devices, particularly those requiring excessive physical maneuvering report higher integrated and peak percentage MVC than interventions that require little involvement of the caregiver, reducing their appeal as a long-term solution [24-26, 52]. This leaves caregivers vulnerable to external compression acting on the spine, which weaken the structure and create extensive discomfort [42].

2.4 Preliminary Research for the Strong Arm Robotic Assisted Transfer Device

The following section provides an overview to the Strong-Arm concept including an overview of participatory action and design research, development of a portable powered transfer devices, an introduction to robotic assisted transfer devices (RATD), and preliminary analysis on the Strong Arm RATD.

Figure 2 Assistive Technology Research and Design Roadmap Reported by Dicianno et al 2018 [2]

2.4.1 Participatory Active Design and Research for Assistive Technology

Because of the large rate of assistive technology abandonment, rehabilitation scientist began implementing Participatory Action Design and Research to develop technologies that alleviated threats of social validity [2, 23, 33, 49, 55, 57]. By receiving direct feedback from potential end users, investigators can develop usable technologies an end user will find appealing. This concept was adopted for mobility devices users and caregivers in order to identify needs and wants of stakeholders in such technologies [2, 23]. The results of this research created a comprehensive roadmap, shown in Figure 2, for future research aims and the technologies applicable to the population of interest, particularly with interest to how modern innovations (i.e. robotics, internet of things, and mobile applications) are implemented to promote independent living [2, 21].

2.4.2 Powered Portable Assisted Device Systems

The desire for advancements in assisted transfer devices was a noticeable outcome from such consumer assessments [2, 7, 23, 30, 33, 34]. A survey study conducted with 1024 mobility device users was delivered to identify priorities for design and development of mobility assistive technologies [2]. Of that sample, approximately 854 (83.3%) of the participants rated “developing portable powered transfers device usable by someone with a disability” as either a critical or important area of research [2]. Additionally, 470 (39%) ranked “human machine interface” as either the most important or important area of technology development while 660 (64%) ranked “transfer devices” as either the most important or an important futuristic invention. In a similar analysis evaluating the provisional perspective of mobility technology (N=161), 103 individuals (64%) envision robotics as a necessity to performing activities of daily living for people with disabilities [23]. When asked about devices to make transfers to and from a wheelchair simple, safe, and pain free, 132 participants (76%) ranked it as the most important or an important futuristic innovation [23].

People with more severe disabilities, as well as their caregivers, are potentially hindered from completing basic activities of daily living that require privacy and dignity [1]. Novel advancements in robotics allows for more sensitivity and self-sufficiency in these individuals, as well as their caregivers, to live more independently, confidently, and self-efficiency [2, 6, 7, 23].

2.4.3 Robotic Assisted Transfer Devices

Robotic assisted transfer devices (RATD) are a novel intervention from rehabilitation sciences, only recently receiving traction with the expanse of robotic applications in healthcare, the rise of disability population, and the desire for ergonomically friendly assistive technology [2, 7, 23, 30-34, 56-59]. Therefore, previous analyses on these technologies are reported from the perspective of engineers and end users, which does not incorporate significant application outcomes [23, 33]. This perception is shared by results of a review performed in Sivakanthan et al 2019, in which current available literature on this technology is in the form of reports on the mechanical and electronical software/hardware as well as stability testing to ensure safety for future testing [33]. Any involvement of potential end users came from focus groups answering survey questions and providing open ended feedback [23, 30, 32].

2.4.4 Evaluation of the Strong Arm RATD Concept

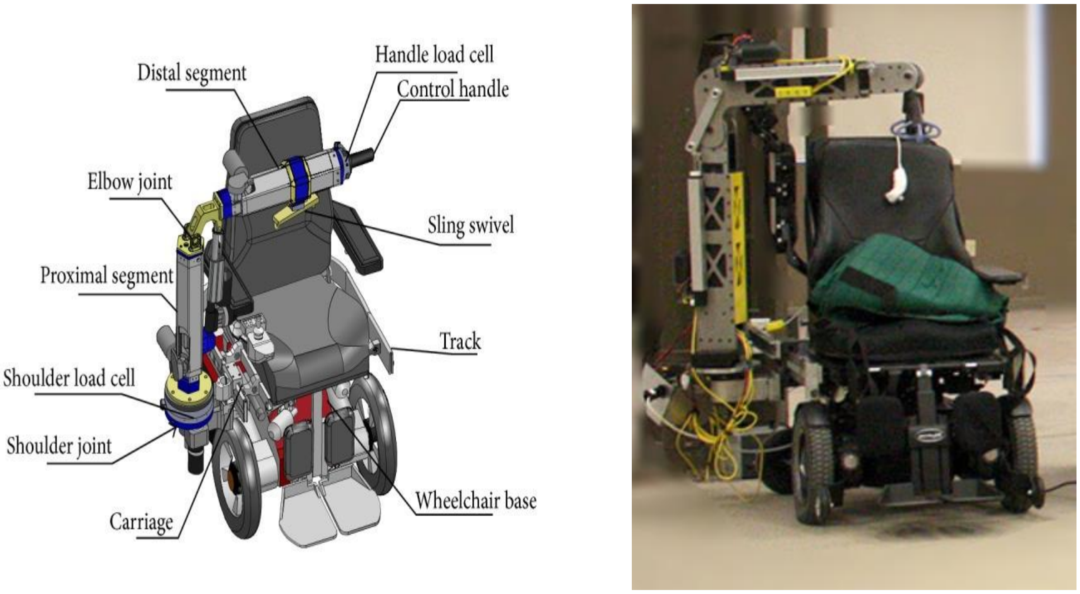


Figure 3 The Strong Arm Robotic Assisted Transfer Device. Left details components of the first version used in Phase I while the right displays the redesigned version for Phase III

Consumer and provisional feedback provided justification to design and develop the Human Engineering Research Laboratories (HERL) RATD, more commonly referred to as Strong Arm [2, 7, 23, 30-34, 56-59]. By incorporating a portable and foldable robot into the transfer process, Strong Arm provides researchers, clinicians, and consumers a novel perspective to the transfer process. Early observational feedback about the concept, design, and purpose proved to be positive. A focus group of 16 power wheelchair users assessing the first-generation Strong Arm believed such a device would make life easier for them (100%) with 13 (81%) agreeing it was important to develop such technology [30]. In another focus group comprised of seven caregivers, five (74%) believed further development of Strong Arm would be important with four (61%) justifying government funding [32]. Such results exert similar optimism to those found in previous surveys and similar studies [2, 23].

Consumer evaluations and focus group testing such as these provide the means to further design and develop such technologies. Such studies did not include usability testing and evaluation of Strong Arm's performance conducting a dependent transfer [5,7]. Up to this point there is no known information regarding the benefits, and barriers, that Strong Arm provides and whether it contributes to a reduction in ergonomic shortcomings associated with a device assisted transfer. Additionally, novel technologies are a challenge to comprehend and a portable robotic transfer device creates an additional challenge of wheelchair accessibility in a common space [60]. There is also a specific degree of anxiety and fear when performing activities of daily using a novel methodology compared to what has become a commonality in their lives [60]. This is particularly true within the geriatric population, where there is a sense of distrust with innovative technologies [61-63]. There is also little information on the cost of this new device. Additionally, consumer and provisionary evaluation describe cost of assistive technology to be the largest barrier to acquiring such equipment to improve quality of life and there is little information [2]. Further testing needs to assess not only the market price for Strong Arm, but also what individuals would be willing to pay for it [2, 23, 33].

3.0 Study Overview

Figure 4 Mechanical floor lift transfer using a lever and compression pump (Top), the prototype of Strong Arm (Middle) and the Strong Arm 2.0 transfer using a joystick (Bottom)

This project was the most encompassing and complete usability assessment of a robotic assisted transfer device by including outcomes assessing usability, biomechanics, and cognitive load. Caregivers conducted dependent wheelchair transfers using the Strong Arm (novel device) and compared those outcomes to transfers conducted using a Hoyer Advance (the clinical standard of care). In comparing transfers using the Strong Arm compared to the gold standard, investigators provided rehabilitation engineers evidence regarding the usability of a robotic assisted transfer device. This in turn bolsters the state of science on injury biomechanics and the incorporation of this technological advancement in healthcare because inclusion potentially provides new methods to reduce the physical load exerted on the caregiver performing a transfer. Additionally, this technology expands the workspace in which transfers are performed with transfer equipment due to the Strong Arm’s ability to fold and tuck behind the user’s wheelchair.

The assessment follows frequently used guidelines to involve potential stakeholders in the development of novel interventions as well as those used when conducting dependent transfers.

This concept of participatory action design includes caregivers and mobility devices users that potentially benefit from application of Strong Arm in and out of a clinical setting.

- **Phase I** compared transfers using a prototype RATD and the clinical standard of care to assess caregiver task load demand, transfer performance, range of trunk flexion, axial rotation, and lateral bend, and distance travelled when conducting performing transfers on a research mannequin at three common transfer surfaces in a lab setting.

- **Phase II** used the feedback provided by participants to further develop a clinically ready Strong Arm for feasibility testing. Additionally, investigators conducted static and dynamic stability testing as to ensure the arm would not cause a C500 Permobil power chair to tip or put a driver/caregiver in danger during clinical testing. No human participants were involved in this phase.

- **Phase III** compared caregiver assisted transfers using a redesigned iteration of RATD used in Phase I with the clinical standard of care as caregivers transferred a care recipient at three transfer surfaces. In addition to the outcomes collected in Phase I, this pilot study also collected usability outcomes using a 10 cm usability survey to obtain feedback from mobility device users about their feelings towards both transfer devices

The project's objectives were accomplished with the following four aims:

Aim 1: Assess self-reported task load demand and usability from the perspectives of caregivers transferring a mannequin using a prototype of the Strong-Arm robotic lift (novel device) compared to a Hoyer Advance mechanical floor lift (clinical standard of care).

- *Hypothesis 1.1:* Investigators are anticipating significantly lower self-reported cognitive load during transfers conducted by the RATD than those conducted by the Mechanical Floor Lift
- *Hypothesis 1.2:* The RATD is anticipated to have a significantly more positive impact than the Mechanical Floor Lift on the transfer maneuver

Aim 2: Assess caregiver flexion/extension, lateral bend, and axial rotation range of motion at three unique phases while performing a dependent transfer using the Strong Arm compared to the Hoyer Advance

- *Hypothesis 2.1:* Significantly reduced range of trunk flexion/extension, axial rotation, and lateral bend is anticipated using the RATD compared to the Mechanical Floor Lift
- *Hypothesis 2.2*: RATD transfers require significantly less pelvic distance travelled, velocity, and acceleration than those using the Mechanical Floor Lift

Aim 3: Assess the usability and task load demand of the Strong Arm 2.0 to perform dependent transfers in real world situations, or conducting transfers on mobility device users, based on qualitative feedback provided by the caregiver and the mobility device user

- *Hypothesis 3.1:* Caregivers will report significantly better scores on the NASA-TLX and usability survey for the RATD versus the mechanical floor lift.

- *Hypothesis 3.2:* Care Recipients report significantly better usability scores during the RATD transfer compared to the mechanical floor lift.

Aim 4: Assess the biomechanics of a newer generation of the Strong Arm (Strong Arm 2.0) on a sample of caregiver conducting dependent wheelchair transfers on mobility device users and compare outcomes to the clinical standard of care

- *Hypothesis 4.1:* Caregivers will experience significantly reduced range of trunk flexion/extension, axial rotation, and lateral bend using the RATD compared to the Mechanical Floor Lift
- *Hypothesis 4.2:* Transfers conducted with the RATD require significantly lower muscle activation in the erector spinae and latissimus dorsi compared to the Mechanical Floor Lift
- *Hypothesis 4.3*: Compared to the Mechanical Floor Lift, the RATD transfers require significantly less distance travelled, time, average instantaneous velocity, and acceleration

4.0 Study 1 – Usability Compared Between a Prototype Robotic Assisted Transfer Device and a Mechanical Floor Lift for Caregiver Assisted Wheelchair Transfers

The ergonomics of assisted Transfer Lifts need to be addressed in order to advance the technology and improve a wheelchair user's ability to live as independently as possible. Implementation of a robotic assisted transfer device (RATD) offers an alternative to such systems. In order to assess risk for transfer related pain and fatigue in the back, the following study compared the trunk angular and pelvis kinematics, in addition to cognitive load and usability, recorded in caregivers performing transfers on a research mannequin using a prototype RATD design and a mechanical floor lift. Formal and Informal Caregivers (N=21) reported significantly reduced range of trunk flexion-extension, lateral bend, and axial rotation as well as pelvic based distance travelled, velocity, and acceleration in transfers using the RATD compared to those using the mechanical floor lift ($p<0.001$). While the concept is promising, further testing is required to address limitations and confirm the concept for application in clinical and non-clinical settings.

4.1 Introduction

Standards implemented by the National Institute of Occupational Safety and Health (NIOSH) suggest a healthcare worker lift no more than 3400 newtons during a typical shift and no more than 35 lb. per lift, similar to the 10kg advised by the International Observational Society (ISO) [16, 17]. To reduce the risk of the 60,000-healthcare related musculoskeletal injuries per year, the Federal Drug Administration and OSHA suggest using Transfer Lifts, a technology accepted as a clinical standard to relieve a caregiver of physical strain during transfers [10, 16, 17]. However, to ensure a safe transfer for both the caregiver and the care recipient, a significant amount of postural adjustments is required by the caregiver when maneuvering a Transfer Lift [5]. The jerk motions in the trunk potentially increase risk for injury to the caregiver and an accident involving the care recipient [34-42].

Floor lifts are not easily transportable and often require two caregivers to operate safely [7, 33]. Floor lifts deter community integration, due to size, and crowd living spaces, making usability during transfers almost impossible in small compact spaces (i.e. an accessible bathroom stall) [12-14, 17, 33]. Though they require less flexion than manual lifting - physically lifting care recipients without assistance from technology - the use of lever and handle system makes a floor lift significantly more physically demanding and less smooth of a transfer than a ceiling lift [24-29]. The movement in the trunk to raise and adjust a care recipient makes the mechanical lift the less appealing of the two systems [24]. The remote-control features of an electronic ceiling lift system ensure no extreme maneuvers in order to transport a care recipient from one surface to another, unlike the mechanical lift [2, 7, 23, 33].

In an analysis between an electronic ceiling lift, a mechanical floor lift, and manual lifting, the ceiling lift required significantly less trunk flexion and bending than the floor lift and the manual lifting, theoretically because of the interface [25]. This indicated the potential for transfer devices that require less movements to complete this maneuver. Participatory action design and research was used to guide development of several innovative patient handling technologies to assist with transfers [2, 7, 23, 33, 52, 56-59, 61, 62]. Robotic assisted transfer devices (RATDs) incorporate powered technology found in immobile ceiling lift systems into a portable system that can be transported to environments that would otherwise be impractical for a floor lift system [52, 57]. One such example is a portable, foldable robot known as Strong Arm. Being a smaller device, the nature of the Strong Arm RATD, would allow for increased workspace, theoretically creating a more efficient system while requiring less motion than the clinical standard [7, 30-33, 56-59]. A focus group of 16 Veterans using power wheelchairs was supportive of further developing the Strong Arm, with 13 (81.3%) agreeing this was important technology, and 16 (100%) agreeing it would make life easier [30]. In a similar focus group comprising of seven caregivers, five (74.3%) said that the development of Strong Arm was important, while six (86.7%) participants said that they would use the device, and all seven (100%) mentioned that it would make their lives easier [32].

The purpose of this study was to compare the trunk based angular and pelvis based distance travelled and time to complete a transfer, in addition to task demand and usability, using an RATD (the novel technology) and a mechanical floor lift (the standard of care) [57, 63]. Using a 67 kg mannequin, investigators anticipated that a sample of caregivers would record significantly lower range of motion in the trunk (i.e. trunk flexion-extension, lateral bend, and axial rotation), in addition to decreased space and average instantaneous velocity and acceleration required to complete a transfer. Additionally, investigators anticipated significantly better scores on the NASA-Task Load Index (NASA-TLX) and a usability for transfers using an RATD compared to a mechanical floor lift. Information collected from this study was intended to be used as justification for a redesign of the RATD for future testing and studies involving caregivers and mobility aid users.

4.2 Methods

Investigators were interested in incorporating feedback from caregivers of various backgrounds and fields. Based on previous literature, these caregivers divided into two groups: formal and informal. Formal caregivers utilize transfer devices on day-to-day basis and because of their contribution to the field as well as their exposure to occupational strain and fatigue, their feedback was vital to the results of the study. Informal caregivers are not always provided with the same training and assistance that their formal counterparts receive, indicating a likelihood that the population is less familiar with device assisted transfers and therefore is more prone to the musculoskeletal discomfort that may result from lifting and moving a care recipient.

4.2.1 Recruitment

Participants are recruited via flyers placed at various research, clinical, and rehabilitation facilities around the area as well as community events dedicated to rehabilitation, disability, and community assimilation. Information was emailed to individuals who qualified for the study and if interest was expressed, the investigator reached to the individual in question. Registries were accessed from the Human Engineering Research Laboratories (HERL), University of Pittsburgh

School of Health and Rehabilitation Sciences, University of Pittsburgh Medical Center, and the Center of Translation Research Institute.

4.2.2 Inclusion and Exclusion Criteria

Caregivers, both formal and informal, were included in the study if (1) they were over the age of 18 years old, (2) were able to donate up to four hours of their time, and (3) had over a year of caregiving experience, which included transferring care recipients. Investigators included participants who never used a transfer lift system and relied on manually lifting participants and students who had over a year of caregiving experience were also included in the study. Caregivers were excluded from the study if they (1) were pregnant and (2) were experiencing, or had experienced, musculoskeletal discomfort they felt would put themselves in harm's way during the protocol.

4.2.3 Descriptive Information

Both caregivers and care recipients provided the investigators with their age, height, and weight. Provided occupational information, education level years of experience and their most frequent caregiving location, such as hospital, inpatient/outpatient clinic, home, or community living center. Care Recipients were asked questions about their age, height, and weight, as well as diagnosis, mobility device they used, and the number of years they used that device. Information on baseline low back pain and occupational fatigue were also collected [65, 66].

4.2.4 Motion Capture Camera and Reflective Marker Set-Up

Motion capture was used to collect reflective marker data from markers placed on caregivers conducting transfers within the clinical space. Twenty motion capture cameras provided by Vicon were used within a 60 x15 foot clinical testing facility at HERL. Cameras were set up to allow for ample capture volume for the manipulation of handling tasks [67]. Therefore, a caregiver was allotted the space to make necessary adjustments during the duration of the transfers. Marker data was captured at 120 Hz.

Caregivers were dressed with passive reflective markers to collect information on joint angles in the trunk, relative to the pelvis, during transfers, based on kinematics protocols from prior patient handling and moving assessments conducted in the same space [67-69]. Markers were placed along specific anatomical landmarks in accordance with the International Society of Biomechanics and prior patient handling and moving protocols [67]. For the data collected in this study, the markers included the left and right acromion, the sternum, xyphoid, the fifth cervical and third and eighth thoracic spinal levels, and the left and right anterior, medial, and posterior iliac spine [68]. Investigators then collected a static capture of a participant to offset angles collected during post processing [67].

4.2.5 Training

Prior to initiation of the study, participants were asked about their experience with transfer lift technology. They were then shown videos developed by clinicians on how to complete an appropriate transfer with the RATD and the Mechanical Floor Lift used in this study. Once each video was finished, participants were then asked to complete a transfer to demonstrate their comfort using the following devices described in more detail below.

4.2.6 Transfer Lifts

Two transfer lift technologies were used in this study: The Strong-Arm prototype (RATD) and the Hoyer Advance (Mechanical Floor Lift).

4.2.6.1 RATD

A prototype of the Strong Arm RATD used for this protocol was a joystick powered robot arm that utilizes five degrees of freedom (DOFs), including shoulder rotation, elbow extension, and elbow raise [30-33; 56-69]. The joystick interface was attached onto the robot as to allow for more direct interaction between caregiver and the transfer device [58]. The joints, activated by actuators powered by the joystick, included force sensors to trigger the beginning and the end of a transfer [31]. The manifold controls of the robot are designed to avoid personal space of the wheelchair user and are only operational when a caregiver directly handles the joystick as to avoid accidental movements [58]. When attached to a power wheelchair along an ambidextrous track, the robot had seven DOFs, thus increasing the workspace area [58]. The track, as well as the foldable feature of the arm, also allowed for storage behind the wheelchair when not in use [58]. The ability to be programmed, as outlined by Jeannis et al 2013 provided position feedback regarding the use of the system which distinguishes this device from other

Figure 5 Prototype Strong Arm RATD interface

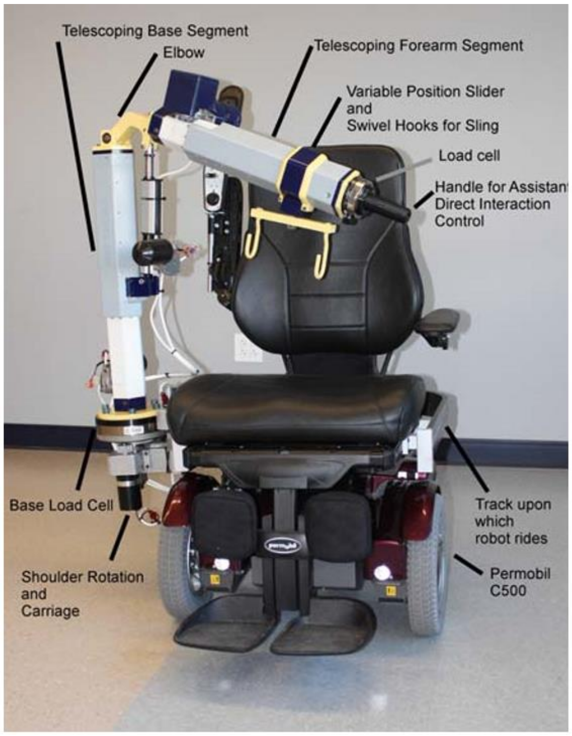


Figure 6 Prototype Strong Arm RATD

transfer devices [31]. Furthermore, the prototype only reduces the range of the power wheelchair by about 10%, providing more travelling distance. Four safety layers, a trained human operator, mechanical, electronic and software controls, ensure the safety of the caregiver as well as the person they are transferring [58]. This includes pinch points and rounded edges at the mechanical layer, a deactivation and limit switches at the electronic layer, and safety limits programmed by the software layer. The range of motion is always restricted which prevents instability during the transfer process [58].

4.2.6.2 Mechanical Floor Lift

The standard of care for this study was the Hoyer Advance (*Joern's Healthcare, 2017)* [7, 33, 63]. The Hoyer Advance is a mechanical floor lift system that relies on a handlebar, crank, and a pump to transfer a care recipient. An adjustable handle controls compressed fluid in the system while a lever is used to pump air into the system. The fluid is released when the handle is adjusted to lower the system onto a transfer surface. Holding a care recipient is a standard sling and harness system. The harnesses are attached to the system

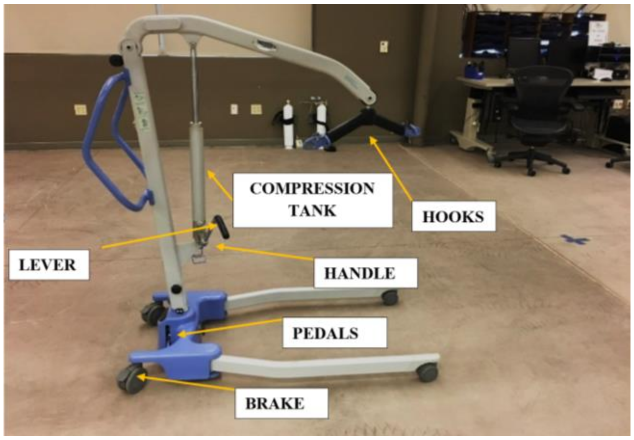


Figure 7 Hoyer Advance Mechanical Floor Lift

by two bilateral hooks which hoist the sling during a transfer. Caregivers pump compression fluid to lift the harness, which holds the individual out of the chair before health care personnel transport them to the destination. Four wheels, two on the legs, and two behind the base, maneuver the system from surface to another with a pedals component to adjust size of the legs when navigating spaces of different size. This system is also parked by two brakes on the hind wheels in order to ensure safety when lifting and placing a participant.

4.2.7 Study Protocol

Once caregivers reported confidence with the transfer device, and investigators and clinical coordinator consented, operation of each device during the transfer portion of the protocol commenced. Three surfaces were used for the purposes of the study: (1) An Accessible Toilet, (2) Therapy Bench, and (3) a Tub Chair.

Figure 8 Transfer Surfaces Used in the Study (from Left to Right: (1) Accessible toilet, (2) Therapy Bench, and (3) Tub Chair

The accessible toilet, 17 inches tall, was placed in a space complying with Americans with Disabilities Act guidelines [70]. Fitness hurdles were used to delineate the useable space. The therapy bench (*Hill)* is a standard 36’’x72’’ adjustable cushioned mat table. The bench was adjusted accordingly. The third surface used for the study was a standard tub chair (*Drive Medical)*, intended to mimic a shower or bathtub

Balanced randomization was used to determine the order of testing (device/surface combination), where caregivers and recipients would conduct three transfers between wheelchairs and surfaces. Transfers were conducted to and from wheelchairs, using both devices at each surface for a total of six transfers to and from a surface, or 36 total transfers. To investigate potential differences in body mechanics during a transfer, investigators asked caregivers to pause after three distinct transfer phases of a transfer, as inspired by a transfer device user manual provided by the Federal Drug Administration [71]. (1) Lift refers the to the vertical raise of a care recipient and ends when the caregiver begins the transfer. (2) Transport refers to horizontal extension and rotation of the transfer device. This phase ends when the caregiver reaches the target surface. (3) Placement is the downward vertical motion of a care recipient safely onto a target surface. At least five minutes were allotted between stations to rest, but caregivers or recipients could take a break at any time during the protocol.

4.2.7.1 Surveys

NASA-TLX is a psychometric test used to assess task load [72]. For the purposes of this study, raw scores (0=task success; 100=task failure) of each domain were compared [73]. Usability feedback about the impact of the transfer device was collected via a 10 cm visual analogue survey (0=Negative Outcome; 10=Positive Outcome) regarding the impact of assistive technology (USAT). The USAT included a section for open ended feedback, where participants provided critiques, and investigators took notes, about the Strong Arm RATD design. A section for individual feedback was also included. Further details on the survey can be found in the Appendix D.

4.2.8 Post Processing

4.2.8.1 Kinematics

Investigators reconstructed dynamic trial data using Vicon Nexus 1.8.5 (*Vicon)* to specifically label reflective markers. Labelling the data provided coordinates, in a three-dimensional plane, of the marker of interest. Data was exported and processed in a customizable Matlab code (*MathWorks, 2017*) from which marker data was shifted to a local coordinate system. Coordinates were used to calculate trunk flexion-extension, lateral bend, and axial rotation in the trunk relative to the pelvis throughout the duration of the dynamic trial [68]. Missing data, occurring from random error or marker occlusion during the trial, were interpolated using spine and pattern filling techniques [74]. Posterior iliac spine markers were averaged to identify a vector in the middle of the pelvis. This vector, selected because of required pelvis stability during a lifting task, was used to obtain the caregiver's position in space and transfer time [75]. Data was exported to a spreadsheet (*Microsoft, 2016)* to calculate the range of motion of joint angles. Space required to complete a transfer, in addition to total transfer phase, a caregiver's average instantaneous velocity and acceleration were calculated from the pelvis vector along the posterior iliac spine. Calculations can be found in Appendix B.

4.2.9 Data Analysis

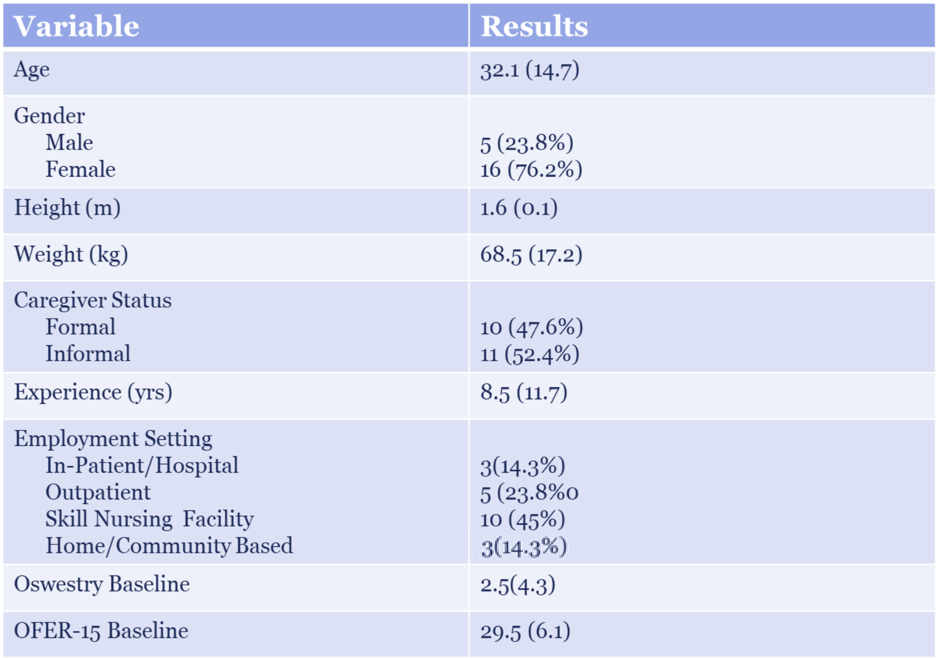
Demographics, EMG, and kinematics data was analyzed using SPSS Version 27 (*IBM, 2019)***.** Means and standard deviations as well as frequencies and percentages were used as measures of central tendency and variation for quantitative and qualitative data respectively**.** Because repeated measures ANOVAs was the desired parametric statistical test, a Shapiro-Wilks test was used to assess for normality, Q-Q plots and histograms for presence of outliers, Mauchly's test for sphericity**.** Outliers and related points were eliminated from the analysis, and a Greenhouse-Geiser test was used for violations in sphericity**.** Missing data, due to random error, in participants that completed more than 80% of the protocol, was compensated for by using the overall study average of that recorded trial, also known as group-mean imputation**.** Participants that completed less than 80% of the protocol were excluded

A four way repeated measures ANOVA was used, due to its robustness to non-normality and alternative tests for sphericity violations (i.e. Greenhouse-Geiser), to detect potential statistical significance (p<.05) in device main effects, from which a sub-analysis of the Bonferroni corrected single pairwise comparisons between device and surface, phase, and/or direction was also analyzed if an interaction effect was also detected**.** A two way repeated measures ANOVA was used for the survey data and a sub-analysis was conducted if an interaction effect was detected. Effect size was determined by Cohen's F, which defined a large clinical effect as a value >0.40.

4.3 Results

A total of 21 caregivers were recruited in the study. Of those 21 participants, twenty (95.2%) completed at least 80% of the protocol and were included in the analysis.

Table 1 Descriptive Statistics for Caregiver Participants (N=21)



Variable	Results
Age	32.1 (14.7)
Gender	
Male	5 (23.8%)
Female	16 (76.2%)
Height (m)	1.6 (0.1)
Weight (kg)	68.5 (17.2)
Caregiver Status	
Formal	10 (47.6%)
Informal	11 (52.4%)
Experience (yrs)	8.5 (11.7)
Employment Setting	
In-Patient/Hospital	3(14.3%)
Outpatient	5 (23.8%o
Skill Nursing Facility	10 (45%)
Home/Community Based	3(14.3%)
Oswestry Baseline	2.5(4.3)
OFER-15 Baseline	29.5 (6.1)

Demographic information, levels of low back pain, and occupational fatigue are displayed in Table 1. Previous statistics report the average caregiver to be a 48-year-old woman who cares for a sick relative. Participants (N=21) were approximately 32.1 years old, predominately female (76.2%) and Caucasian (76.2%). Ten (47.6) were formal caregivers while 11 (51.4%) were informal in nature. Seven of the twenty-one participants had a master's or another post graduate degree (33.3%), worked full time (47.6%) who had an average Oswestry score of 2.48 (4.30) and an OFER-15 score of 29.49 (6.05). One of the participants was unable to complete the protocol and therefore, their responses were not incorporated. Additional demographic information can be obtained in Greenhalgh et al 2019 [59].

4.3.1 Range of Flexion-Extension, Lateral Bend, and Axial Rotation

Table 2 Trunk Range of Motion (a) Mean (SD) and (b) Statistical (P) and Clinical Effect Size (F)

Range of Motion	RATD	Mechanical Floor Lift	P	F
Flexion-Extension	8.7 (8.7)	15.6 (13.2)	**<0.001**	1.38
Lateral Bend	8.2 (7.4)	14.6 (12.0)	**<0.001**	2.12
Axial Rotation	25.0 (19.8)	50 (34.2)	**<0.001**	1.98

RATD transfers required significantly lower flexion extension than those using the Mechanical Floor Lift (p<0.001, F=1.38), as well as reduced range of lateral bend (p<0.001; F=2.12) and axial rotation (p<0.001; F=1.98).

No interaction effects were detected for any of the independent variables.

4.3.2 Pelvic Adjustments

Table 3 Transfer Space and Speed (a) Mean (SD) and (b) Statistical (P) and Clinical Effect Size (F)

Pelvic Adjustments	RATD	Mechanical Floor Lift	P	F
Distance Travelled (m)	3.54 (1.65)	6.91 (3.93)	**<0.001**	2.15
Instantaneous Velocity (m/sec)	0.035 (0.017)	0.095 (0.017)	**<0.001**	1.98
Instantaneous Acceleration (*m/sec^2*)	3.54 (1.65)	9.89 (3.93)	**<0.001**	2.05

RATD transfers required significantly lower distance travelled than those using the Mechanical Floor Lift (p<0.001, F=2.15), as well as reduced instantaneous velocity (p<0.001; F=1.98) and axial rotation (p<0.001; F=2.05).

No significant interaction effects were detected for each of the independent variables of interest.

4.3.3 NASA-TLX

Table 4 NASA-TLX Outcomes (a) Mean (SD) and (b) Statistical (P) and Clinical Effect Size (F)

Domains	RATD	Mechanical Floor Lift	P	F
Mental Demand	25.0 (16.8)	16.7 (9.8)	0.09	0.46
Physical Demand	9.7 (8.6)	35.6 (19.2)	**<0.001**	1.57
Temporal Demand	19.4 (14.8)	22.6 (16.7)	0.28	0.28
Performance	17.6 (12.9)	17.5 (12.6)	0.97	0.01
Effort	16.3 (13.5)	33.4 (23.4)	**0.002**	0.86
Frustration	15.9 (14.4)	19.1 (16.7)	0.24	0.23

RATD transfers required significantly less physical demand to complete successfully (p<0.001; F=1.56) compared to those using a Mechanical Floor Lift and required significantly less effort (p=0.002; F=0.86).

No interaction effects were coupled with significant main effects.

4.3.4 Caregiver Usability

Table 5 Usability Outcomes (a) Mean (SD) and Statistical Significance (P) and Clinical Effect Size (F)

Impact Variables	RATD	Mechanical Floor Lift	P	F
Back Pain	9.9 (0.2)	9.7 (0.7)	0.18	0.38
Shoulder Pain	10.0 (0.0)	9.7 (0.7)	0.08	0.53
Discomfort Intensity	9.3 (0.4)	7.2 (2.4)	**0.001**	1.12
Discomfort Frequency	8.3 (2.0)	6.3 (2.7)	**0.001**	0.89
Ease	7.7 (1.8)	6.4 (2.0)	**0.01**	0.67
Efficiency	7.8 (1.7)	6.0 (2.1)	**0.01**	0.85
Caregiver Safety	8.6 (1.4)	7.4 (1.5)	**0.01**	0.72
Care Recipient Safety	7.3 (2.3)	6.5 (2.2)	0.11	0.38
Fatigue	9.3 (0.6)	6.4 (2.3)	**<0.001**	1.40
Appeal	6.9 (2.5)	6.2 (2.3)	0.20	0.31

The RATD had a significantly more positive impact on transfer related discomfort intensity (p=0.001, F=1.12) and frequency (p=0.001; F=0.89) than the Mechanical Floor Lift. A significantly more positive impact was also detected for ease (p=0.01; F=0.66) and efficiency (p=0.01, F=0.85) using the RATD compared to the Mechanical Floor Lift in addition to caregiver safety (p=0.01; F=0.72) and fatigue (p<0.001, F=1.40).

An interaction effect was detected for transfer ease, where RATD transfers had a more positive impact on transfer ease at the toilet (p=0.003; F=0.78) and tub char (p=0.003; F=0.80). Additionally, transfer efficiency reported an interaction effect with RATD transfers reporting a significantly more positive impact on transfer efficiency at the toilet (p=0.001; F=0.89) and tub chair (p=0.05; F=0.49) surfaces.

4.4 Discussion

RATDs are a novel technology utilizing robotics to improve the quality of care delivery for both caregivers and care recipients by improving transfer device ergonomics and reducing risk of injury. While actual wheelchair users were not included in this study, we tested experienced caregivers, because of the physical and mental demands they endure transferring a care recipient. Following study completion, analysis revealed positive results in favor of using a prototype of the RATD over the clinical standard of care mechanical lift. We accepted our hypothesis that caregivers would report significantly lower task demand and better usability using the RATD and accepted our hypotheses that the RATD would require a significantly lower range of flexion-extension, lateral bend, and axial rotation, in addition to a lower distance travelled and average instantaneous velocity and acceleration.

4.4.1 Trunk Mechanics

Caregivers in previous biomechanics and epidemiology literature implicated repetitive manual transfers to be uncomfortable and strenuous, especially performed multiple times a day [9-

15]. This is primarily due to the awkward body mechanics, such as extensive flexion and rotation, required to complete a successful transfer while ensuring the care recipient's safety [10, 11]. NIOSH insists that a caregiver raise no more than 35 pounds in a single lift [17]. However, the trunk flexion and rotation required to complete a transfer leads to compressive and sheer forces on the caregiver when transferring, increasing the risk of injury in the lower back [46]. By virtue of being the clinical standard, the mechanical floor lift meets the NIOSH criteria as a safe alternative to manual lifting and thus can reduce the need for harmful body mechanics during a transfer, including excessive repetitive flexion [7, 16, 17, 33, 63].

Results of this report indicated significant promise for RATDs as an equally effective standard of care as the mechanical floor lift. Compared to the clinical standard, caregivers during the Strong Arm RATD transfers reported approximately half the range of flexion (8.7 deg vs 15.6 deg) and rotation (25 deg vs 49 deg) required to conduct a transfer compared to a clinical standard of care. This indicated significantly lower flexion and rotation ranges of motion were required to complete the difference phases of a successful assisted transfer at all phases of a transfer. Activation of the Strong Arm interface, the joystick, required 3 Newtons of force or less, unlike a mechanical floor lift, which required 86 N in initial push force to initiate a transfer on a concrete surface similar to our clinical testing center [29, 30, 58]. This tells us the RATD potentially reduced exposure to the physical strain and fatigue caused by compressive and sheer forces implicated in muscle failure and long-term pain acting on the L5/S1 Center of Mass, though more research is needed to incorporate kinetic feedback during a transfer with this device [34, 38, 48].

4.4.2 Transfer Space and Speed

The RATD covered approximately 3.5 total meters of space compared to the 6.9 for the total transfer. This was the equivalent to about a third of the average instantaneous velocity (approximately .0035 m/sec vs .0095 m/sec) and acceleration (3.5 m/sec^2 vs 9.5 m/sec^2) across all three transfer phases. The lower distance travelled and average instantaneous velocity and acceleration required confirmed the hypothesis that a portable RATD would require significantly less distance covered and speed to complete a transfer to and from a wheelchair. The mechanical floor lift required lifting the mannequin out of a chair, adjusting the “swan like” legs with a pedal, and wheeling it to a target destination [63]. This could potentially be problematic when transferring a care recipient, while attempting to navigate the floor lift through a smaller, compact spaces (i.e. the accessible bathroom). Such a maneuver risks bumping a care recipient into walls or doors if used incorrectly. Additionally, the transfer related anxiety, and stress of their job, may force the caregiver to expedite the transfer, which leads to potentially fatal accidents [5, 15, 32, 60]

A caregiver positioned the Strong Arm directly on a wheelchair, which was lined up next to the target surface [58]. Caregivers thus do not require additional space to complete the transfer [30-33, 56-59]. Therefore, they may feel safer or condiment to control/manage a care recipient and therefore perform transfers at a more comfortable average velocity and acceleration [58]. This was reported in Greenhalgh et al 2019 [58]. A device with these capabilities potentially reduces the risks of serious accidents that occurs due to drops and falls and poor patient handling and moving [5, 15]. The safety aspect, in addition to the smooth nature of the transfer, explains the appeal of portable powered transfer lift technologies, which is addressed in Dicianno et al 2019 as well as Burkman et al 2017 respectively [2, 23, 32].

4.4.3 Task Demand and Usability

Users in this study felt reduced physical demand and physical discomfort to use the RATD device compared to the Hoyer. This may be explained in part by the Strong Arm requiring different kinematics, space and time requirements in comparison to the Hoyer [50]. Such findings hold promise to advance the safety of a transfer lift system by reducing the risk of drops during transfers that require less space, and adjustments, necessary to complete them successfully. Results of the current research confirmed outcomes analyzed in companion reports released by Greenhalgh et al 2019 and Blaauw et al 2020 [58, 59].

Though such technology reduced the physical demand and effort required to complete a transfer, it should be noted that, while not statistically significant, mental demand was higher using the RATD than the Mechanical Floor Lift. Caregivers found the interface difficult to understand and perform with, despite introduction before protocol initiation. This is potentially the result of familiarity with pre-existing technology (i.e. Mechanical Floor Lift) and attempting to understand a novel technology (RATD), while on the job. This interface, which was directly attached to the robot, also allowed for little room for adjustments a caregiver could make during a transfer, which in turn increased cognitive demand of the task. This was echoed in self-reported data in which, caregivers described the rigidity of the interface to be a frustrating aspect of the RATD and that future developments needed to advance the interface and the space allowed to transfer.

4.4.4 Study Limitations

While study design intended to minimize biases and additional limitation, such factors should be discussed. Outcomes were based on a small convenience sample of caregivers which were relatively younger than those in the general population. Future studies should include a more diverse sample of caregivers, as well as care recipients, which would improve the generalizability of the device in its implication to improve the transfer process. Survey data detected a ceiling effect in both the USAT and NASA-TLX, indicating a potential inaccurate representation of a caregiver's usability and cognitive demand perspective. Analyzing range of joint motion, and not peak joint angles, was justified, because the interest was focused on comparing two devices with human machine interface designed to reduce the intensity of a transfer, compared to manually lifting [66, 67]. Peak joint angle could be used in future analyses about whether the reduced ROM is correlated to higher, or lower, peaks and self-reported discomfort over a longer period. Furthermore, while our outcomes showed that participants showed reduced movement and adjustments using the RATD some participants verbalized critiques with the prototype design. Specifically, they were concerned about the positioning and operation of the joystick [2, 23, 33, 61]. This is a common issue even with the use of Hoyer lifts and requires all caregivers and personal attendants to be cautious when placing the person into the wheelchair, as the arm that supports the sling should not touch the wheelchair user's face. Modifications to the area included a cradle with soft foam to cover the metal hooks. The RATD also experienced hardware and software difficulties which required three participants to return at later dates to finish the protocol.

5.0 Study 2 – Ergonomic Assessment of a Robotic Assisted Transfer Device For Caregiver Assisted Transfers Conducted On a Care Recipient and Compared to a Mechanical Floor Lift

The RATD represents a novel methodology to reduce strain, maneuvering, and cognitive load a caregiver experiences when conducting transfers on a mannequin. However, caregivers who used this new technology report suggested adjustments regarding the robot's human machine interface and shape as to improve transfer efficiency and comfort for care recipients. The purpose of this study was to test a redesigned RATD and compare its ergonomics during a transfer to those of a mechanical floor lift. Caregivers (N=28) were recruited to conduct transfers while investigators recorded trunk kinematics and muscle activation, cognitive load, and usability. As opposed to Study 1 which used a mannequin, caregivers in this study partnered with, and transferred, a mobility device user (N=28), which provided the opportunity to garner usability feedback from the perspective of a care recipient. Results indicated promise for the RATD as caregivers reported significantly lower range of flexion (p=0.001), lateral bend (p<0.001), and axial rotation (p=0.001), in addition to reduced muscle activation in the back, and physical demand (p=0.004) and discomfort frequency (p=0.01). However, critiques with the interface, the harness and sling, and the robot's rigidity indicated more work is needed before introducing this technology to a larger market.

5.1 Introduction

Ergonomics and clinical biomechanics literature suggest caregivers, conducting assisted transfers on people with disabilities, are exposed to prolonged periods of awkward posturing and higher muscle activation because of the frequency and intensity of prolonged load bearing [9-15]. When conducting the transfer manually, meaning without assistance, a caregiver spends about 25% of their time in a flexion position greater than 30 degrees, indicating significant periods of repetitive, awkward bending and rotation in the trunk [11, 12, 46]. Twisting and stretching of the waist requires a larger range of lateral bend and axial rotation in the trunk, which are implicated in 51% of caregivers as a source of discomfort experienced in their occupation [12, 13]. Healthcare is one of the leading fields for at risk non-fatal work related injuries, which includes 60,000 annual cases of musculoskeletal disorder and 62% of caregivers reporting pain in the low back due to repeated transfers [9, 10]. Approximately 50% of healthcare providers report low back pain annually and 80% throughout their careers [13]. When addressing healthcare related task demands including assisted transfers, ICU nurses report physical demand and effort scores between 60-70 (out of 100), indicating task failure [50].

Transfer lift technologies were introduced to reduce the load placed on a caregiver conducting an assisted transfer manually [7, 24-29, 33]. Floor and ceiling, or overhead, lifts are two common examples used for comparison to manual lifting in prior literature [24-29]. Both devices significantly reduced the range of repetitive bending and rotation in the trunk and as such were reviewed favorable by caregivers [25]. They were also found to reduce peak and integrated electromyography (EMG) in the lower back, specifically the erector spinae [52]. Such technology is beneficial to reducing the biomechanical risk factors for low back pain, such as compressive and shear forces acting on the lumbar spine, that a caregiver may be repeatedly exposed to during a typical eight to 12 hour shift [24, 25, 29]. However, certain lift systems, such as the floor lift, do not eliminate repetitive maneuvering and task demand required by caregivers during a transfer [7, 33].

End users find portable, powered transfer technologies to be an innovation of importance, in addition to the inclusion of robots into independent living [2, 23]. A robotic assisted transfer device (RATD) is one such innovation considered to address these requests [2, 23, 30-33, 56-59]. Previous research on the Strong Arm RATD confirmed this technology significantly lowered self-reported discomfort frequency and physical task demand from caregivers compared to a mechanical floor lift [59].

RATD design had several shortcomings that impeded its ability to act as a less stressful transfer methodology. It was important to address appropriate human machine interface to improve performance of assistive technology [7, 23, 61]. Because the joystick was attached directly to the robot, caregivers implied care recipients would feel cramped and thus not have the space to get comfortable when being transferred [58].

The opinion of a care recipient is also crucial for the RATD long-term success as a novel clinical standard. As of 2010, there were over two million wheelchair users in the United States, which includes 810,000 power wheelchair and scooter users [1]. Investigators utilizing participatory action design and research to develop novel assistive technologies recruited this demographic to assess the appeal of novel interventions [2, 7, 23, 30-33, 55, 62]. Dicianno et al 2018 interpreted focus group feedback from a sample of 1024 mobility aid users, who emphasized the importance of powered portable Transfer Lifts, such as the Strong Arm RATD [2].

Approximately 64% of 181 providers (i.e. caregivers) believed incorporating robotics to complete basic ADLs was an important innovation [23]. When asked specifically about the Strong Arm, a focus group of 16 power wheelchair users said this technology would make their lives easier (N=16), agreeing that it was an important technology to develop (N=13) [30].

Despite the promise of RATDs as a methodology to advance the clinical standard, there has been no clinical testing analyzing caregiver biomechanics during RATD transfers with a care recipient. There is also no care recipient feedback of the transfer experience available. The purpose of this study was to compare caregiver assisted transfer body mechanics and muscle activation in the trunk between an RATD and a mechanical floor lift. We also collected self-reported feedback from our caregivers in addition to our care recipients. Investigators predicted that based on marker data collected from motion capture cameras, the RATD would require a significantly smaller range of trunk flexion, lateral bend, and axial rotation in addition to significantly reduced transfer space, time, and average instantaneous velocity and acceleration. We also predicted transfers with the RATD would require reduced activation of muscles in the back during a transfer, specifically the erector spinae and latissimus dorsi than one conducted by the mechanical floor lift. As such caregivers would report significantly better scores on the NASA-TLX and a usability survey for RATD transfers compared to the mechanical floor lift and likewise, care recipients would report significantly better scores for the RATD than the mechanical floor lift.

5.2 Methods

The study was approved by the Veterans Affairs Pittsburgh Healthcare System Institutional Review Board and was a generalized cross-sectional convenience sample of both people who use wheelchairs and caregivers.

5.2.1 Recruitment

Participants are recruited via flyers placed at various research, clinical, and rehabilitation facilities around the area as well as community events dedicated to rehabilitation, disability, and community assimilation. Information was emailed to individuals who qualified for the study and if interest was expressed, the investigator reached to the individual in question. Registries were accessed from the Human Engineering Research Laboratories [HERL], University of Pittsburgh School of Health and Rehabilitation Sciences, University of Pittsburgh Medical Center, and the Center of Translation Research Institute.

5.2.2 Inclusion and Exclusion Criteria

5.2.2.1 Caregivers

Caregivers, both formal and informal, were included in the study if (1) they were over the age of 18 years old, (2) were able to donate up to four hours of their time, and (3) had over a year of caregiving experience, which included transferring care recipients. Investigators included participants who never used a transfer lift system and relied on manually lifting participants and students who had over a year of caregiving experience were also included in the study. Caregivers were excluded from the study if they (1) were pregnant and (2) were experiencing, or had experienced, musculoskeletal discomfort they felt would put themselves, and the mobility device user, in harm’s way during the protocol.

5.2.2.2 Care Recipients

Care Recipients, or mobility device users, were included in the study if they (1) were over the age of 18, (2) weighed less than 82 kg (~180lbs), (3) used a mobility device over three times a week. Exclusion criteria included (1) existing history of ulcers, abrasions, fractures, or deformities that would hinder a comfortable and/or safe transfer, (2) clinical discretion against the exercise, (3) the participant was pregnant.

5.2.3 Study Setup

5.2.3.1 Descriptive Information

Both caregivers and care recipients provided the investigators with their age, height, and weight. They also provided occupational information, education level years of experience and their most frequent caregiving location, such as hospital, inpatient/outpatient clinic, home, or community living center. Care Recipients were asked questions about their age, height, and weight, as well as diagnosis, mobility device they used, and the number of years they used that device.

5.2.3.2 Electromyography

Electromyography was collected using Telemyo DTS 2400T (*Noraxon)* computer software and non-invasive sensors sampled at 1500 Hz [75, 76]. Transmitter boxes attached to electrodes, collected muscle activation data from NA+ adhesive pads placed on the skin over the muscle of interest [67]. Four sensors were placed along bilateral muscles in the back, specifically the erector spinae and the latissimus dorsi in accordance with Basmajian et al 1980 and Noraxon [75, 76]. The erector spinae sensors were placed laterally on the first lumbar level of the spine [75]. The latissimus dorsi sensors were placed in the shape of a 25-degree oblique angle below the inferior tip of the scapula, half the distance between the spine and the lateral edge of the torso [75]. Investigators then had caregivers perform an exercise to activate the maximum voluntary contraction (MVC) of the muscle of interest. In the first exercise, which activated the left and right erector spinae, the participant lied on their stomach and arched their back up to the ceiling. The second and third exercise, which activated the left and right latissimus dorsi respectively, required the participant to remain on their stomach while rotating their arm inward and then upward, thumb to the floor, while an investigator provided resistance to the forearm.

5.2.3.3 Motion Capture and Reflective Markers

Motion capture was used to collect reflective marker data from markers placed on caregivers conducting transfers within the clinical space. Twenty motion capture cameras provided by Vicon were used within a 60 x15 foot clinical testing facility at HERL [67]. Cameras were set up to allow for ample capture volume for the manipulation of the transfer devices. Therefore, a caregiver was allotted the space to make necessary adjustments during the duration of the transfers. Marker data were captured at 120 Hz.

Caregivers were dressed with passive reflective markers to collect information on joint angles in the trunk, relative to the pelvis, during transfers. Markers were placed along specific anatomical landmarks in accordance with the International Society of Biomechanics and prior patient handling and moving protocols conducted in the clinical space [67-69]. For the data collected in this study, the markers included the left and right acromion, the sternum, xyphoid, the fifth cervical and third and eighth thoracic spinal levels, and the left and right anterior, medial, and posterior iliac spine [68]. Investigators then collected a static capture of a participant to offset angles collected during post processing [67].

5.2.3.4 Training

Prior to initiation of the study, participants were asked about their experience with transfer lift technology. They were then shown videos developed by clinicians on how to complete an appropriate transfer with the RATD and the Mechanical Floor Lift used in this study. Once each video was finished, participants were then asked to complete a transfer to demonstrate their comfort using the following devices described in more detail below.

5.2.4 Transfer Lifts

5.2.4.1 RATD

The RATD used for the study was the Strong Arm RATD, updated from a prototype version described in pervious literature [30-33, 56-59]. Much like the prototype, Strong Arm was mounted along the side of a C500 Permobil power wheelchair along a track in line with research conducted on the Personal Mobility and Manipulation Appliance (PerMMA) [2, 23, 57]. The track increases Strong Arm's range of motion and allows the robot to fold and tuck behind the user's device [57]. Device's ability to conduct caregiver transfers in smaller compact spaces with one person is better than those conducted by a Hoyer, which carries more bulk and is difficult to fit into compacted areas [57]. The portability as well as its range of motion provide the ability for Strong Arm to act as a transport device in a non-clinical setting [57]. One significant addition to the concept not described in prior studies was the advancement of the human machine interface, an important aspect when considering powering and maneuvering power

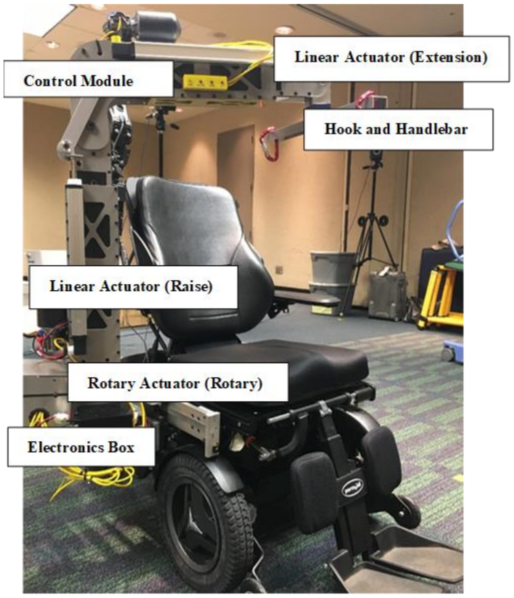


Figure 11 Second Generation Strong Arm RATD Components

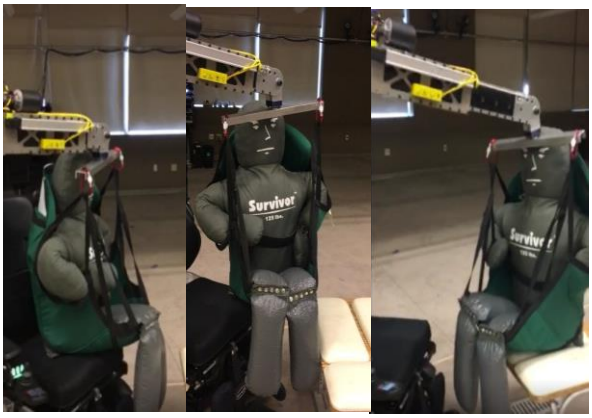


Figure 10 Transfer using Strong Arm

Figure 9 Components of the Second Generation Strong Arm

wheelchairs and compliant technologies [2, 23, 57, 61]. Controlling this generation of Strong Arm is a repurposed Nunchuck, a joystick commercially operating the Nintendo Wii (*Nintendo*). Designed to switch between the modes while maximizing space to perform a transfer, the Nunchuck ensured that the user was only able to transfer when pressing down on a specific key, the bottom "Z" button. This safety trigger prevented unintended motion, thus acting as an additional safety mechanism.

5.2.4.2 Mechanical Floor Lift

The mechanical floor lift for this study was the Hoyer ® Advance (*Joern's Healthcare, 2018)* [7, 33, 63]. The Hoyer Advance is considered a standard of care in accordance with International Organization of Standard (ISO) and the National Institute of Occupational Safety and Health (NIOSH) [16, 17, 63]. Hydraulic mechanical floor lift system that relies on a handlebar, crank, and pump to manipulate compressed fluid to safely lift, transfer, and place a care recipient to and from two different surfaces [63].

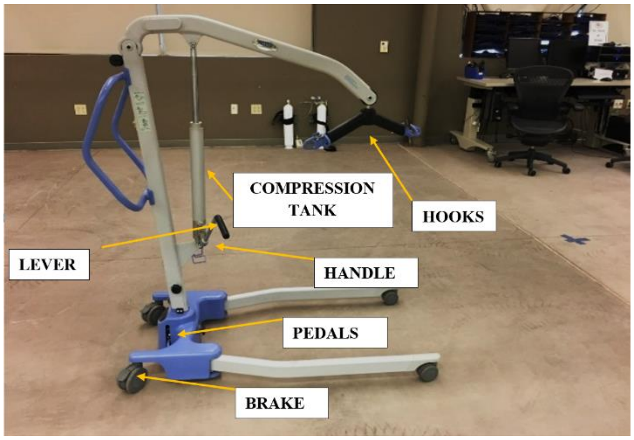


Figure 12 Hoyer Advance Mechanical Floor Lift

5.2.5 Study Protocol

Once caregivers and care recipients reported confidence with the transfer device, and investigators and clinical coordinator consented, operation of each device during the transfer portion of the protocol commenced. Three surfaces were used for the purposes of the study: (1) An Accessible Toilet, (2) Therapy Bench, and (3) a Tub Chair.

Figure 13 Transfer Surfaces Used in the Study (from Left to Right: (1) Accessible toilet, (2) Therapy Bench, and (3) Tub Chair

The accessible toilet, 17 inches tall, was placed in a space complying with Americans with Disabilities Act guidelines [70]. Fitness hurdles were used to delineate the useable space. The therapy bench (*Hill)* is a standard 36’’x72’’ adjustable cushioned mat table. The bench was adjusted accordingly to avoid abrasion of the care recipient’s lower body. The third surface used for the study was a standard tub chair (*Drive Medical),* intended to mimic a shower or bathtub

Balanced randomization was used to determine the order of testing (device/surface combination), where caregivers and recipients would conduct three transfers between wheelchairs and surfaces. Transfers were conducted to and from wheelchairs, using both devices at each surface for a total of six transfers to and from a surface, or 36 total transfers. To investigate potential differences in body mechanics during a transfer, investigators asked caregivers to pause after three distinct transfer phases of a transfer, as inspired by a transfer device user manual provided by the Federal Drug Administration [70]. (1) Lift refers the to the vertical raise of a care recipient and ends when the caregiver begins the transfer. (2) Transport refers to horizontal extension and rotation of the transfer device. This phase ends when the caregiver reaches the target surface. (3) Placement is the downward vertical motion of a care recipient safely onto a target surface. At least five minutes were allotted between stations to rest, but caregivers or recipients could take a break at any time during the protocol

5.2.5.1 Surveys

NASA-TLX is a psychometric test used to assess task load [72]. For the purposes of this study, raw scores (0=task success; 100=task failure) of each domain were compared [73]. Usability feedback about the impact of the transfer device was collected via a 10 cm visual analogue survey (0=Negative Outcome; 10=Positive Outcome) regarding the impact of assistive technology (USAT). The USAT included a section for open ended feedback, where participants provided critiques, and investigators took notes, about the Strong Arm RATD design. Additional information on our post transfer surveys can be found in Appendix D.

5.2.6 Post Processing

5.2.6.1 Peak Percentage and Integrated Maximum Voluntary Contraction

EMG and MVC data were exported via spreadsheets for further filtering in a customizable Matlab Code adapted from a prior patient handling and moving study conducted at HERL (*MathWorks, 2017*) [67, 75, 76]. Data was filtered twice (1) with the Telemyo and (2) with the Matlab code. Data was filtered in the Matlab code using a fourth order lowpass, bandpass Butterworth filter with a cutoff low of 10 Hz and a high of 400 Hz. This data was then down sampled to 100 Hz for analysis. The dynamic EMG data was normalized in relation to the MVC collected before the study protocol [75, 76]. Normalized outcome was multiplied by 100 to collect a percentage of the EMG data in relation to the MVC (100%) [75, 76]. Peak Percentage MVCs (pMVC), peak activation of the muscle, and integrated MVC (iMVC), area under the curve, were exported to, and stored in, a Microsoft Excel Spreadsheet (*Microsoft, 2016).* Calculations of our EMG data can be found in Appendix A.

5.2.6.2 Kinematics

Investigators reconstructed dynamic trial data using Vicon Nexus 1.8.5 (*Vicon)* to specifically label reflective markers. Labelling the data provided coordinates, in a three-dimensional plane, of the marker of interest. Data was exported and processed in a customizable Matlab code (*MathWorks, 2017*) from which marker data was shifted to a local coordinate system. Coordinates were used to calculate trunk flexion-extension, lateral bend, and axial rotation in the trunk relative to the pelvis throughout the duration of the dynamic trial [68]. Posterior iliac spine markers were averaged to identify a vector in the middle of the pelvis. This vector, selected because of required pelvis stability during a lifting task, was used to obtain the caregiver's position in space and transfer time [77]. Data was exported to a spreadsheet (*Microsoft, 2016)* to calculate the range of motion of joint angles. Distance covered to complete a transfer, in addition to total transfer phase, a caregiver's average instantaneous velocity and acceleration were calculated from the pelvis vector along the posterior iliac spine. Calculations can be found in Appendix A.

5.2.7 Data Analysis

Demographics, EMG, and kinematics data was analyzed using SPSS Version 27 (*IBM, 2019)***.** Means and standard deviations as well as frequencies and percentages were used as measures of central tendency and variation for quantitative and qualitative data, respectively. Because repeated measures ANOVAs was the desired parametric statistical test, a Shapiro-Wilks test was used to assess for normality, Q-Q plots and histograms for presence of outliers, Mauchly's test for sphericity. Outliers and related points were eliminated from the analysis, and a Greenhouse-Geiser test was used for violations in sphericity. Missing data, due to random error, in participants that completed more than 80% of the protocol, was compensated for by using the overall study average of that recorded trial, also known as group-mean imputation. Participants that completed less than 80% of the protocol were excluded.

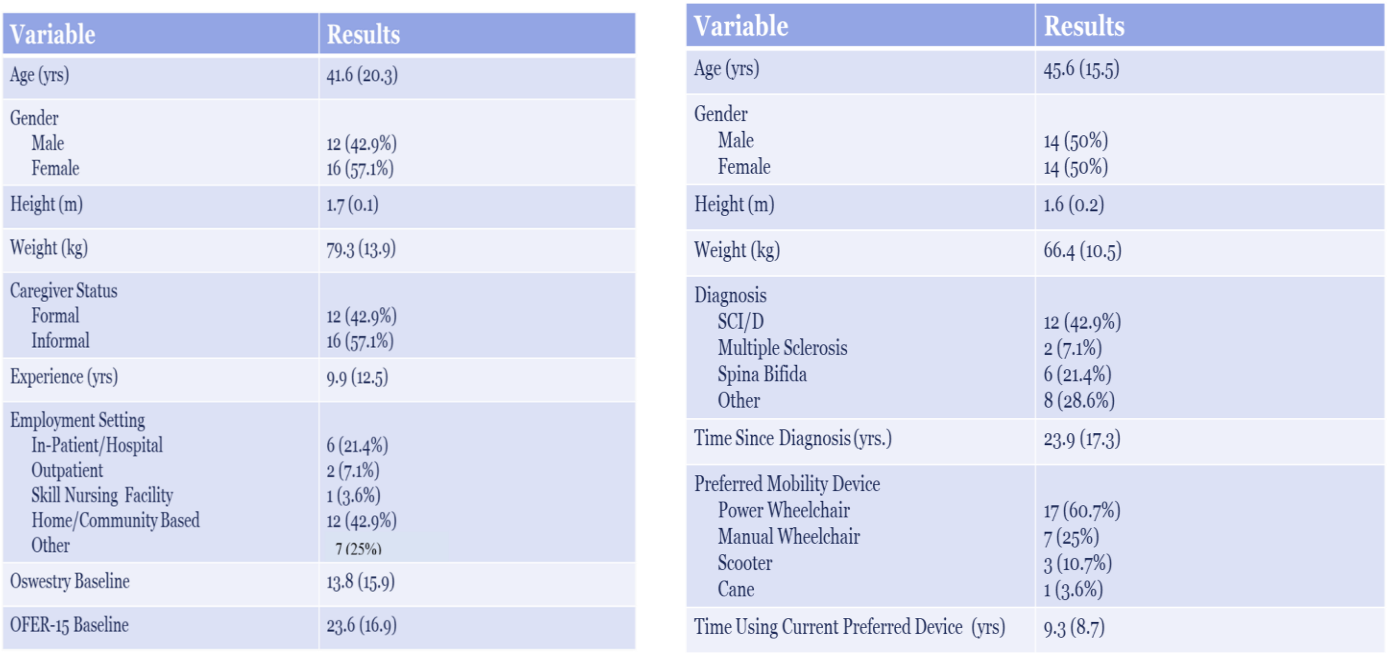
A four way repeated measures ANOVA was used, due to its robustness to non-normality and alternative tests for sphericity violations (i.e. Greenhouse-Geiser), to detect potential statistical significance ($p<.05$) in device main effects, from which a sub-analysis of the Bonferroni corrected single pairwise comparisons between device and surface, phase, and/or direction was also analyzed if an interaction effect was also detected. A two-way repeated measures ANOVA was used for the survey data and a sub-analysis was conducted if an interaction effect was detected. Effect size was determined by Cohen's F, which defined a large clinical effect as a value >0.40.

5.3 Results

Twenty-eight caregiver + care recipient dyads (N=56) were recruited and consented for this study, of whom 26 (94%), completed 80% of the protocol with both the RATD and the Mechanical Floor Lift.

5.3.1 Demographics

Table 6 Descriptive Feedback from (a) Caregivers (N=28) and (b) Care Recipients (N=28)



Variable	Results
Age (yrs)	41.6 (20.3)
Gender Male Female	 12 (42.9%) 16 (57.1%)
Height (m)	1.7 (0.1)
Weight (kg)	79.3 (13.9)
Caregiver Status Formal Informal	 12 (42.9%) 16 (57.1%)
Experience (yrs)	9.9 (12.5)
Employment Setting In-Patient/Hospital Outpatient Skill Nursing Facility Home/Community Based Other	 6 (21.4%) 2 (7.1%) 1 (3.6%) 12 (42.9%) 7 (25%)
Oswestry Baseline	13.8 (15.9)
OFER-15 Baseline	23.6 (16.9)

Variable	Results
Age (yrs)	45.6 (15.5)
Gender Male Female	 14 (50%) 14 (50%)
Height (m)	1.6 (0.2)
Weight (kg)	66.4 (10.5)
Diagnosis SCI/D Multiple Sclerosis Spina Bifida Other	 12 (42.9%) 2 (7.1%) 6 (21.4%) 8 (28.6%)
Time Since Diagnosis (yrs.)	23.9 (17.3)
Preferred Mobility Device Power Wheelchair Manual Wheelchair Scooter Cane	 17 (60.7%) 7 (25%) 3 (10.7%) 1 (3.6%)
Time Using Current Preferred Device (yrs)	9.3 (8.7)

The caregivers were on average 41.6 +/- 20.3 years old, 1.7 +/- 0.1 meters and 79.3 +/- 13.9 kg. Sixteen (57.1%) were women who worked full time (N=9 (40.9%)) as informal caregivers (N=16 (57.1%)) for an average of 9.9 +/- 12.5 years in the home/community (N=12 (42.9%)).

Care recipients were on average 44.6 +/- 15.5 years old, 1.6 +/- 0.2 meters tall, and weighed 66.4 +/- 10.5 kgs. There was an even split between men and women (N=14 (50%)), with predominately Spinal Cord Injury/Disease (N=12 (42.9%)) diagnosed 23.9 +/-17.3 years prior. When asked about preferred mobility aid, 17 (60.7%) reported their power wheelchair, which they were using the previous 9.3 +/- 8.7 years.

5.3.2 Range of Trunk Flexion-Extension, Lateral Bend, and Axial Rotation

Table 7 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for Range of Motion in the Trunk (deg)

Range of Motion	RATD	Mechanical Floor Lift	P	F
Flexion-Extension	15.9 (12.9)	24.6 (18.7)	**<0.001**	1.10
Lateral Bend	19.3 (15.1)	25.5 (19.1)	**<0.001**	0.90
Axial Rotation	36.4 (28.6)	47.5 (34.9)	**0.001**	0.82

RATD transfers required a significantly lower range of flexion extension than those using the Mechanical Floor Lift (p<0.001, F=1.18), as well as a reduced range of lateral bend (p<0.001; F=0.90) and axial rotation (p<0.001; F=0.82).

An interaction effect was detected for axial rotation. The RATD transfers required significantly reduced range of axial rotation during RATD transfers than the Mechanical Floor Lift transfers at the accessible toilet (p=0.003; F=0.70) and the rehabilitation bench (p=0.002; F=0.71). Range of axial rotation was significantly lower during RATD transfers during lift (p<0.001; F=1.06) and transport phases (p=0.001; F=0.62).

5.3.3 Pelvic Space Required, Time, Average Instantaneous Velocity and Acceleration

Table 8 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for Transfer Space, Time, and Average Speed

Pelvic Adjustments	RATD	Mechanical Floor Lift	P	F
Distance Travelled (m)	3.50 (1.93)	7.53 (4.01)	**<0.001**	1.86
Time (sec)	20.80 (6.77)	18.39 (6.53)	**0.04**	0.56
Instantaneous Velocity (m/sec)	0.012 (0.002)	0.020 (0.002)	**0.01**	1.75
Instantaneous Acceleration (m/sec^2)	1.16 (0.58)	2.16 (0.67)	**<0.001**	2.38

RATD transfers required a significantly smaller space than those using the Mechanical Floor Lift (p<0.001, F=1.86), as well as reduced average instantaneous velocity (p=0.01; F=1.75) and acceleration (p<0.001; F=2.38).

An observed interaction effect between device and phase found significantly reduced distance travelled during RATD transfers at the lift (p<0.001; F=1.18) and transport (p<0.001; F=2.94) phases compared to the Mechanical Floor Lift. RATD transfers required a significantly reduced average instantaneous velocity, compared to the Mechanical Floor Lift transfers, during the transport (p<0.001; F=2.77) phases.

Transfer time was significantly higher during RATD transfers than during Mechanical Floor Lift transfers (p=0.04, F=0.56). RATD transfers required significantly more time to complete at the rehab bench (p=0.004; F=0.84) and tub chair (p=0.03; F=0.62) surfaces than during Mechanical Floor Lift transfers. RATD transfers required significantly more time to complete at the transport (p=0.01; F=0.80) and placement (p=0.02; F=0.64) surfaces than during Mechanical Floor Lift transfers. Significantly more time was required to complete RATD transfers back to the wheelchair (p=0.01; f=0.72) than the Mechanical Floor Lift.

5.3.4 Peak Percentage Maximum Voluntary Contraction

Table 9 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for pMVC in the Back (%)

Muscle	RATD	Mechanical Floor Lift	P	F
Erector Spinae (R)	32.0 (32.9)	45.5 (31.5)	**0.001**	0.92
Erector Spinae (L)	22.7 (20.9)	47.8 (38.5)	**<0.001**	1.03
Latissimus Dorsi (R)	18.1 (17.8)	42.0 (28.9)	**<0.001**	1.56
Latissimus Dorsi (L)	32.3 (21.0)	39.8 (24.2)	0.10	0.40

Peak MVC was significantly lower during RATD transfers in all four muscles except for the left latissimus dorsi (p=0.10; F=0.40).

An interaction effect between device and each surface found significantly lower right erector spinae muscle activation was required to complete a transfer at each surface, except for the rehab bench (p=0.37; F=0.22).

An interaction effect between device and phase found significantly reduced left and right erector spinae muscle activation for all phases except for the right erector spinae during the placement phase (p=0.35; F=0.23).

5.3.5 Integrated Maximum Voluntary Contraction

Table 10 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for iMVC in the Back

Muscle	RATD	Mechanical Floor Lift	P	F
Erector Spinae (R)	5289.7 (4856.7)	5626.8 (3836.3)	0.56	0.13
Erector Spinae (L)	3679.7 (3122.1)	6284.7 (4649.3)	**0.001**	0.85
Latissimus Dorsi (R)	2571.2 (2560.3)	4187.6 (2893.8)	**0.01**	0.68
Latissimus Dorsi (L)	3518.0 (2533.6)	4206.9 (2773.9)	0.07	0.42

Integrated MVC was significantly lower during RATD transfers in the left erector spinae (p=0.001; F=0.85), and right latissimus dorsi (p=0.01; F=0.68). An interaction effect between device and surface found significantly lower muscle activation in the left erector spinae by surface, but not in the right muscle at the accessible toilet (p=0.12; F=0.38), the rehabilitation bench (p=0.75; F=0.08), and the tub chair (p=0.85; F=0.04). Latissimus dorsi iMVC was significantly lower during RATD transfers at the accessible toilet in both the right (p=0.01; F=0.63) and the left sides (p=0.01; F=0.63).

Integrated MVC was significantly lower during the lift phase in the right (p<0.001; F=1.10) and left (p<0.001; F=1.03) erector spinae muscles and during the lift phase in the right (p<0.001; F=0.96) and left (p<0.001; F=0.96) latissimus dorsi muscles.

An interaction between device and direction found the latissimus dorsi iMVC was significantly smaller during transfers to the surface in both the right (p=0.02; F=0.55) and left muscles (p=0.02; F=0.55).

5.3.6 Task Load Demand

Table 11 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for Raw Score NASA-TLX outcomes

Impact Variables	RATD	Mechanical Floor Lift	P	F
Mental Demand	35.9 (25.6)	14.7 (13.5)	**<0.001**	1.10
Physical Demand	17.1 (18.4)	39.9 (27.7)	**0.004**	0.68
Temporal Demand	26.4 (25.5)	30.5 (28.6)	0.54	0.13
Performance	26.4 (25.5)	30.5 (28.6)	0.53	0.13
Effort	29.3 (23.3)	39.6 (29.0)	0.25	0.24
Frustration	34.8 (26.6)	33.3 (31.8)	0.87	0.03

RATD transfers required significantly less physical demand to complete successfully (p<0.004; F=0.68) compared to those using a Mechanical Floor Lift.

An interaction effect was detected for physical demand, which was significantly lower during transfers at the accessible toilet (p<0.001; F=0.73) and the tub chair (p=0.01; F=0.65)) using the RATD compared to the Mechanical Floor Lift.

RATD transfers showed significantly more mentally demand (p<0.001; F=1.10) than Mechanical Floor Lift transfers.

5.3.7 Caregiver Usability

Table 12 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for Caregiver USAT scores

Impact Variables	RATD	Mechanical Floor Lift	P	F
Back Pain	8.2 (2.3)	7.5 (3.4)	0.40	0.17
Shoulder Pain	9.3 (1.0)	7.6 (3.0)	**0.01**	0.66
Discomfort Intensity	8.0 (2.2)	7.3 (2.9)	0.28	0.23
Discomfort Frequency	8.5 (1.8)	6.9 (2.8)	**0.01**	0.63
Ease	6.1 (2.8)	6.1 (2.9)	0.98	0.01
Efficiency	6.4 (2.5)	6.3 (2.8)	0.88	0.03
Caregiver Safety	7.2 (2.7)	6.8 (2.4)	0.61	0.11
Care Recipient Safety	8.1 (1.7)	7.1 (1.9)	0.15	0.31
Fatigue	7.1 (2.7)	6.2 (3.1)	0.26	0.23
Appeal	6.1 (3.0)	5.6 (3.4)	0.69	0.18

The RATD had a significantly more positive impact on transfer related shoulder pain (p=0.01; F=0.66) and discomfort frequency (p=0.01, F=0.63).

The RATD had a significantly more positive impact for discomfort frequency at the accessible toilet (p=0.002, F=0.73) and rehab bench (p=0.01; F=0.60).

In the written section, caregivers reported device usability as a facilitator, but critiqued the human machine interface and the robot’s range of motion as barriers and areas for future research. Learning to operate a Wii Nunchuck, specifically one adapted from a novel video game system, while also performing a transfer was complicated for several participants.

5.3.8 Care Recipient Usability

Table 13 Means (SD), Statistical Significance (P), and Clinical Effect Size (F) for Care Recipient Usability

Impact Variables	RATD	Mechanical Floor Lift	P	F
Appeal	6.7 (3.3)	5.4 (3.8)	0.17	0.28
Comfort	6.6 (2.6)	7.3 (2.4)	0.22	0.25
Discomfort Frequency	8.3 (2.2)	8.1 (2.7)	0.70	0.08
Discomfort Intensity	8.1 (2.4)	8.2 (2.5)	0.90	0.03
Efficiency	6.7 (2.6)	7.2 (2.6)	0.35	0.19
Performance	7.0 (2.7)	7.4 (2.3)	0.44	0.16
Safety	7.3 (2.7)	8.3 (1.9)	0.07	0.38
Stability	7.0 (2.7)	7.3 (2.2)	0.48	0.14

No significant main effects were reported for care recipient usability.

Care recipients reported usability as a facilitator, but critiqued their personal comfort, the device's stability, lack of space between their body and the robot, and their inability to use the device during the study as areas of future research.

5.4 Discussion

The purpose of this study was to compare the impact of an RATD and a mechanical floor lift on caregiver trunk body mechanics and muscle activation during a transfer. Using guidance provided by caregivers in prior studies, the Strong Arm RATD was redesigned to address concerns with the human machine interface, the flexibility, and the aesthetic appeal of the product [2, 23, 30, 32, 58]. Because results indicated significantly smaller ranges of flexion-extension, lateral bend, and axial rotation, our hypothesis, that the RATD would reduce the range of trunk movement compared to the mechanical floor lift, was correct for most transfer scenarios. Because results of transfer distance covered, average instantaneous velocity and acceleration were significantly reduced during RATD transfers compared to the mechanical floor lift in most of our scenarios, our second hypothesis was correct for most transfer scenarios. Since most of our transfer scenarios showed significantly smaller muscle activation in the erector spinae and latissimus dorsi, our hypothesis that the RATD would require significantly smaller muscle activation was also correct. Based on results finding significantly better scores using Strong Arm RATD than the Hoyer Advance mechanical floor lift in most of our transfer scenarios, our hypothesis that caregivers would report significantly better scores during RATD transfers was correct. However, we rejected our hypothesis that care recipients would record significantly better scores for the RATD compared to the mechanical floor lift. Results confirmed the RATD as a promising transfer lift system that matches, if not exceeds the facilitators provided by a mechanical floor lift (the clinical standard) [16, 17]. While results confirm promise of an RATD as an equal, if not more favorable transfer device, several aspects of the results indicate the need for additional inquiry and research before introducing the RATD as a new clinical standard.

5.4.1 Trunk Body Mechanics

The RATD reduced the intensity of movement in flexed positions by approximately 10 degrees (RATD: 15.7 deg; Mechanical Floor Lift: 25 deg). Such findings indicate a less intense range of flexing in the trunk when transferring a care recipient. Previous literature states that the odds of low back pain decrease by 41% in hospitals that provide transfer lift interventions due to lower exposure to biomechanics risk factors that occur during manual lifting [53]. However, rolling floor lift technologies are difficult to transfer in compact spaces and non-clinical environments, thus requiring a larger range of trunk motion, compared to automated systems, to adjust the lift when transferring [2, 23, 25, 33].

It can be assumed that the RATD, an automated system that lowered the range of flexion-extension in addition to lateral bend (19.3 deg vs 25.5 deg) and axial rotation (36.4 deg vs. 47.5 deg), allowed caregivers to maintain more stable body mechanics, which potentially prevented exposure to dangerous compressive and sheer force acting on the L5/S1 Center of Mass in the low back [46, 57]. While a mechanical floor lift is accepted as a standard to reduce power and moment that a caregiver would expose themselves to during a manual transfer, having an ability to stand adjacent to a care recipient in an upright position, rather than flexed, is potentially the reason for lower physical demand, and thus reduces the risk of a severe accident due to inappropriate transfer mechanics or tips and falls out of an assistive device [2, 23, 24, 29, 58]. This is particularly useful at surfaces in smaller, or more compact spaces, such as the simulated bathroom, which the caregiver did not need to rotate their trunk nearly as much as the mechanical floor lift transfer.

5.4.2 Transfer Space, Time, and Speed

Results of this assessment found significantly reduced distance required by a caregiver to complete a transfer. Across all three phases, the caregiver covered approximately 3.5 meters using an RATD while the mechanical lift transfer covered approximately 7.5 meters. Significantly reduced distance required during the lift and transport phases indicated that the care recipient is not “dangling” over as much open area compared to the mechanical floor lift transfer, which often requires more space due to its shape and size [7, 63].

Theoretically, because the caregiver does not experience the same physical task demand as manual lifting or rolling floor lifts, they are less rushed to complete a transfer with the Strong Arm [25, 58]. This is suggested due to the significantly lower average instantaneous velocity and acceleration during a longer transport phase. For instance, there was increased amount of time needed to seat the care recipient comfortably back to the power wheelchair, which is more difficult to transfer into because of the bulk and awkward positioning of the arm rests and electronics [78]. Because of the reduced load placed on caregivers, there is a reduced urge to complete more difficult transfers in a quicker fashion that would hinder their safety or the safety of a wheelchair user [78]. However, Strong Arm required significantly more time to complete a transfer based on main effects of different transfer scenarios. Reducing the time needed to complete a transfer is essential, because caregivers may be rushed to assist fellow caregivers or people with disabilities and resort to more hazardous methodologies to expedite a transfer [25]. A quick transfer methodology that does not temporally stress the caregiver, is a necessary advancement required for future research.

5.4.3 Muscle Activation in the Back

Compared to the mechanical floor lift, our RATD reported significantly smaller pMVC and iMVC outcomes in the erector spinae and latissimus dorsi in one or both bilateral muscle groups. ISO guidelines suggest exerting no more than 3400 Newtons during a typical shift, following similar guidelines by NIOSH which prefer a healthcare worker lift no more than 35lbs per lift [16, 17]. Although we are unable to equate EMG to force, the results of this study indicated that the RATD requires less muscle activation to complete various transfer scenarios. This may mitigate the force impacting the lower back and thus meets clinical criteria described by NIOSH and ISO [3, 16, 17, 25]. Furthermore, when coupled with the smaller range of motion in the trunk to complete a transfer, particularly flexion and rotation, we would have reason to believe the RATD is more clinically impactful to reduce the risk factors for excessive load bearing placed on the lumbar spine [16, 17]. This, along with reduced average instantaneous velocity, acceleration, and longer transfer time, suggested that the caregiver may not be experiencing the same level of task related demand and discomfort that would otherwise compromise the safety of themselves and their care recipients [13, 58].

The muscle activation in the erector spinae during RATD transfers was like that found in a ceiling lift transferring a 92 kg simulated patient in a prior ergonomics study that, despite being longer, required a smaller iMVC than a floor lift [25]. Unlike a ceiling lift, which was favored to a floor lift due to the smoother nature of the transfer, the RATD is a portable, powered system that can be used outside of a clinical, or confined, space, as seen in significant iMVC outcomes at our accessible toilet and the tub chair surfaces [2, 24, 57]. As such, the RATD's ability to act as a portable powered transfer device implicated it as a methodology that not only reduces biomechanical adjustments required to complete a transfer, but also advances the transfer lift concept for non-clinical environments [2, 23, 30, 57]. Future research coupling kinematics and muscle activation with kinetics is needed in order to identify a direct link to reduced forces (i.e. compressive and sheer) and an RATD [24, 26-29].

5.4.4 Caregiver Feedback

The mechanical floor lift reported mean main effect of 39.9 +/- 27.7 for NASA-TLX sections on physical demand and 15.7 +/- 18.4 for the RATD, which represented a large clinical effect size between both devices. This suggests that the caregiver experienced significantly lower physical demand during the assisted transfer task on a care recipient when using the RATD compared to using the mechanical floor lift. In survey feedback provided by Santaguida et al 2005, caregivers ranked overhead ceiling lifts as more favorable than floor lifts, because of the smooth transfer they experienced [24]. Written feedback provided by the caregivers in this study indicated similar promise, because such technology would reduce the persistency of pain caregivers experienced as part of their profession, which conversely reduces the risk for injury and the demand faced in the workplace [24, 50, 58].

Mental demand based on NASA-TLX questions was significantly higher during RATD transfers when compared to mechanical lift transfers, which was reported with a large clinical effect size. This outcome, coupled with open-ended feedback, suggests this was due to the human machine interface. The Wii Nunchuck was significantly more difficult to understand and operate than that of the Mechanical Floor Lift. Because the caregiver reported no significant differences in ease, efficiency, and task performance, in addition to open-ended feedback, it appeared they were concerned with learning to use the interface, and less on transfer performance. It is possible that it impacted their impression of the RATD during care recipient transfers compared to mannequin transfers. Additional research needs to account for age and years of experience when using an advanced robot for transfers. Approximately 72% of caregivers are on average over the age of 45 and take care of an older parent [79. 80]. Older caregivers had concerns when using related equipment, because of the lack of familiarity and therefore trust with the system [2, 61].

Our caregivers were on average younger than 45 years old. The oldest was 84 years old, who reported frustrations understanding the interface. Caregivers noted the RATD did not provide enough range of motion to conduct a stress-free transfer, which impacted safety and stability. Based on open-ended feedback, and non-significant scores for task effort and safety, caregivers reported feeling cramped and overwhelmed by the technology as they attempted to maneuver their care recipient, who, if heavier in weight, were impacted to due to slight instability during a transfer. Future redesign efforts to address this issue are necessary, particularly to ensure unwavering safety and stability of the care recipient as they are hoisted from the Strong Arm off the surface.

No significant differences were reported with temporal demand using the NASA-TLX. As mentioned earlier, fewer time pressures potentially reduced the urge to complete a transfer as quickly as possible. Provided appropriate performance, it is important that a caregiver have a mechanism that completes a transfer as quickly and efficiently as possible [25]. It is likely they will favor hazardous but understandable methodologies rather than use something that may be more demanding, which puts themselves, and their care recipients, at risk for long term harm to expedite transfers in the short term [5, 15, 50]. The RATD has the potential to provide a highly efficient transfer but needs further development to overcome cognitive demands imposed on caregivers.

5.4.5 Care Recipient Feedback

We rejected our hypothesis that the care recipient would report significantly higher usability scores on the USAT during RATD transfers compared to mechanical floor lift transfers. Similar critiques were raised from the care recipient as the caregiver. Specifically, these participants suggested advancing Strong Arm’s compatibility to transfer with more comfortable slings compared to the clinically accepted one required in the study [2]. Additionally, the proximity of a care recipient's head to the robot made them feel cramped, which affected their perception of the comfort they experienced as part of the transfer. This was particularly a problem with taller or lengthier individuals.

In one common response from our open-ended feedback, care recipients also suggested advancing the Strong Arm RATD for independent transfers as well. In a study of caregiver burden, 23% of power wheelchair users did not require assistance from a caregiver during a transfer and power wheelchair users made up 60.7% of our care recipients (N=17) [81]. Depending on the nature of an individual's diagnosis, a portable, automated device with the appropriate safety mechanisms would potentially allow for a power wheelchair user to transfer on their own while lowering the risk of inappropriate handling and moving and transfer related tips and falls [2, 5, 15, 58]. Such data could also be confirmed in prior consumer assessments noting the Strong Arm RATD would make life easier and that portable powered transfer devices are an important area of research [2, 23, 30, 32]. Further research is required to confirm such desires.

5.4.6 Study Limitations

While study design intended to minimize biases and additional limitations, such factors should be discussed. Though six dyads (N=12) were recruited and tested at the 2018 National Veterans Wheelchair Games in Orlando, FL, in addition to the Pittsburgh region (N=44), future studies should include a more expansive and diverse sample as to improve generalizability of the outcomes. Additional selection bias stemmed from professional relationships with caregivers and care recipients and their affiliations with previous research conducted with the investigators in this study.

Reporting biases potentially occurred from a Hawthorne Effect. Because this study took place in a clinical setting, observed by clinical researchers asking participants to pause during transfer phases, it is possible caregivers acted differently conducting a transfer compared to their normal routine in the natural environment. Reporting biases also potentially stemmed from random equipment failure which occurred throughout the study. The RATD experienced hardware and software difficulties that created scenarios in which an investigator briefly intervened to assist with a transfer and fix an error associated with the electronics. Additionally, EMG equipment failure and low-quality motion capture data created concerns that data would not reflect actual outcomes. However, this was only a concern in 10% of both reportable EMG and kinematics outcomes.

6.0 Conclusions and Future Directions

As the United States population continues to grow older and disability becomes socially accepted outside of the clinical space, it is imperative to advance technologies that improve quality of care delivery as well as the wellbeing for both care recipients and the caregivers that provide assistance [1, 2, 19, 23]. Tasks, such as the transfer, are physically and emotionally, strenuous for a caregiver, who confront several ergonomic barriers when applying novel interventions, particularly Transfer Lifts, to this task [19, 20, 50]. Recent consumer feedback revealed the importance of developing portable powered Transfer Lifts that reduce the effects of these barriers, with a Robotic Assisted Transfer Devices (RATD) representing an opportunity to advance the clinical standard and the quality of care delivery [2, 23, 30, 32, 33, 57]. While potential end users provided feedback via focus group, the robot had not been tested for clinical scenarios. The purpose of this project was to compare the ergonomics of an RATD (Strong Arm) and a clinical standard (Hoyer Advance Mechanical Floor Lift) while garnering feedback to further develop the technology.

6.1 Project Summary

Phase I was a proof of concept study, in which caregivers (N=21) transferred a research mannequin to and from a wheelchair and three surfaces essential for rehabilitation and independent living. Investigators recorded caregiver range of trunk flexion-extension, lateral bend, and axial rotation, in addition to pelvic distance travelled, velocity, and acceleration, cognitive load, and usability. Based on comparisons with the Mechanical Floor Lift, transfers using the Strong Arm required significantly less range of trunk motion as well as pelvic adjustments and was reported to be less physically demanding and a more appeal transfer methodology.

While outcomes from Phase I provided promise to the RATD as a new clinical standard, caregivers were concerned with the equipment's human machine interface (the joystick) as well as the comfort level a care recipient would experience during a transfer. Following a redesign and upgrade to the prototype (Phase II), an ergonomics study (Phase III) compared the same biomechanics outcomes as Phase I, in addition to electromyography, cognitive load, and usability in caregivers (N=28) using the RATD (Strong Arm) and a clinical standard (Hoyer Advance Mechanical Floor Lift) transferring a care recipient partner (N=28) to and from a wheelchair and three target surfaces. Results of the study, which reported significantly reduced flexion and bending, muscle activation in the back, and physical demand further confirmed the RATD as a promising new clinical standard to reduce risks of work related physical strain and improve quality of life for both caregivers and their care recipients.

6.2 Impacts of Demographics and Other Descriptive Information

While the results of both studies reported optimistic outcomes for this technology, further research is necessarily to declare RATDs as a new clinical standard. The effects of descriptive factors were not controlled for in this following project. For instance, previous research reports that hand dominance was shown to influence alteration of physiological and mechanical properties of muscles in that direction [82]. In theory, a caregiver conducting transfers may experience differences in muscle activation based on the direction from which they conduct transfers. Because the following studies recruited significantly more right-handed users, controlling hand dominance would have minimal impact. However, future research that recruits caregivers with characteristics like those found in the population should consider this as a confounding variable.

Additionally, informal caregivers, students, or novice paid clinicians may report different outcomes between the clinical standard and a novel piece of technology, especially amongst those who may be older and less familiar with an interface similar to the Wii Nunchuck [2, 7, 23, 33, 79, 80]. Confounding effects of gender, age, and caregiving expertise may also require further investigation. As for care recipients, it was clear those who were taller had more difficulty adjusting during a transfer and were likely to verbally express discomfort with their experience during both Mechanical Floor Lift and RATD transfers. Further research should adjust for height, and related demographics, that potentially have an impact on the comfort a care recipient experiences using portable transfer equipment [2, 23, 83].

6.3 Inquiries into the Transfer Process

More information can be provided about the transfer process as well. As we analyzed only the transfer portion of patient handling, there was no information on the biomechanics and cognitive load recorded when fitting the mannequin, or the care recipient, in the sling and adjusting them comfortably at the target surface [8, 77]. We were mainly interested in the repetitive motion of the transfer and thus focused on range of motion and not joint angle peaks. This potentially has significant impacts on the biomechanics of the RATD compared to the Mechanical Floor Lift, depending on which one requires more demand for ensuring the comfort of a care recipient [24-29, 50]. It was also reported iMVCs and pMVCs were lower over a consistently longer amount of time than more hazardous methodologies [25]. Future work with the RATD should invest resources into the amount of time spent in these biomechanical “danger zones,” referring to the longer, repetitive periods of physical demand a caregiver experiences as part of the transfer process [46, 50]. This would provide more insight into the effectiveness of an RATD for caregivers who are conducting multiple transfers over the duration of shift work or in the home with a loved one. Additional information should assess the RATD biomechanics on exposure to external forces acting on the L5/S1 Center of Mass. This potentially provides direct evidence for injury biomechanics in healthcare and compares such outcomes for novel transfer methodologies.

6.4 Knowledge for Consumer Assessment

Both caregivers and care recipients voiced concerns with aspects of the design, namely the human machine interface as well as the robot’s ability to extend a transfer across a wider space [2, 23, 61]. The interface was confusing and while the updates were able to create more space between the caregiver and care recipient, the caregiver reported a significantly higher mental demand using the RATD compared to the Mechanical Floor Lift. This indicated more work is required that invests in the usability of different human machine interfaces, an area of research both caregivers and care recipients endorsed in Voice of the Consumer and Provider studies [2, 23]. A future study should further design and develop an interface that is understandable to a sample that would potentially benefit from robotic technologies [2, 23, 30, 32 61]. Caregivers also voiced concern with the range of motion provided by the system. Though the RATD was usable on both sides of a power wheelchair, caregivers critiqued that if degrees of freedom could be expanded, primarily the elbow raise and shoulder rotation features, to allow for more maneuverability, then the RATD would be significantly easier to use. This is a necessary area to address, because clinical researchers would occasionally need to interfere with the protocol to adjust the care recipient at a target surface, while not creating biases that could result from the caregiver's biomechanics.

6.5 RATDs for Independent Transfers

Additionally, research should also incorporate more feedback on the ergonomics of a transfer from the perspective of a care recipient who would benefit from powered transfer equipment [2, 78]. The comfort of the transfer equipment should be addressed. Many of the care recipients voiced displeasure with the sling and harness transfer methodology, the standard for both a Mechanical Floor Lift and the RATD transfers. Specifically, it made them feel cramped and less in control during the transfer process. Further work needs to be accomplished to develop a safe, but comfortable, sling and harness system that a care recipient can adjust with ease and experience more flexibility while transferred. Furthermore, several care recipient participants were eager to use the technology by themselves. An RATD, in this case Strong Arm, is potentially usable by a care recipient, depending on the nature of their diagnosis. This could create a situation in which care recipient, particularly one who can use their upper extremities, can transfer independently while less at risk for upper extremity injuries related to a transfer [2, 3]. However, further work is required to understand differences in different diagnoses on human machine interface interactions, upper extremity biomechanics using these interface, and cognitive load/difficulty [78].

This ensuing research would be used as justification for effectiveness trial in a clinical, or non-clinical, space to prove the Strong Arm RATD as an effective transfer technology to reduce the risk of work related injury in caregivers, advance independent living conditions for their care recipients, and improve the quality of care delivery and quality of life for both parties. Clinicians can use the information gathered from this project, and related studies, to compare and contrast the RATD system with clinical standards of a hospital or nursing home and assess both short term and long term outcomes at individual, community, and legislative levels [33]. This includes comparisons among individual Mechanical Floor Lifts, Electronic Floor Lifts, and Ceiling Lifts and link outcomes with those found with Manual Lifting. It would be intriguing to identify if results of RATD transfers would align with those found with typical ceiling lifts, or if there would be any significant difference between those two surfaces as well [66]. It also includes comparisons regarding the costs as well as risks versus benefits of using a Transfer Lift, like the RATD, compared to a Mechanical Floor Lift and Manual Lifting. Previous consumer outcomes report the costs to be an important aspect into how people chose their technology and that inquiring into how much one is willing to spend on a piece of equipment provides justification for its inclusion into a market place, such as Medicare/Medicaid [2, 23, 24, 33, 84].

With this research, the Strong Arm RATD has the potential to be introduced to a larger audience on a healthcare market and provide care both care recipients and caregivers require to transition into a new normal.

Appendix A Biomechanics Analysis

The following appendix gives an overview of the formulas used to calculate the clinical biomechanics used in the study.

Appendix A.1 Peak Muscle Activation (%MVC) is the peak voltage of muscle activation identified throughout the task compared to the MVC multiplied by 100

$$peak\ muscle\ activation = \frac{Experimental\ EMG}{MVC} * 100$$

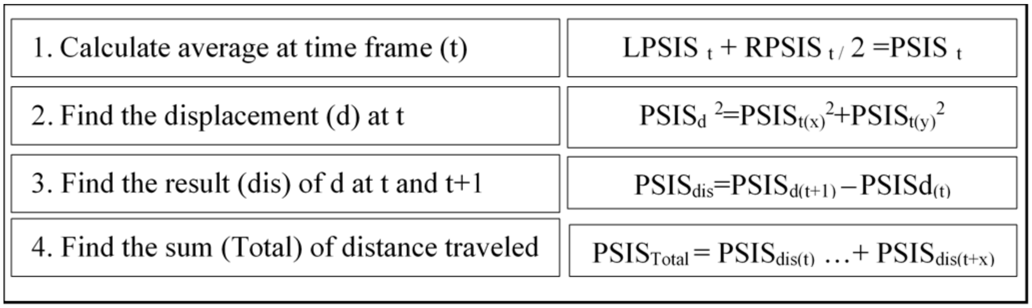
Figure 14 Peak Percentage MVC

Appendix A.2 Integrated Muscle Activation (iMVC) is the sum of the percentage muscle activation over the duration of the task

$$\boldsymbol{iMVC = \int_{time} \left| \frac{experimental\ EMG}{MVC} \right|}$$

Figure 15 Integrated MVC

Appendix A.3 Pelvic Distance Travelled: The following equation calculated distance travelled at the pelvic by taking the midpoint of the two posterior iliac spine markers



1. Calculate average at time frame (t)	$LPSIS_t + RPSIS_{t} / 2 = PSIS_t$
2. Find the displacement (d) at t	$PSIS_d{}^2 = PSIS_{t(x)}{}^2 + PSIS_{t(y)}{}^2$
3. Find the result (dis) of d at t and t+1	$PSIS_{dis} = PSIS_{d(t+1)} - PSISd_{(t)}$
4. Find the sum (Total) of distance traveled	$PSIS_{Total} = PSIS_{dis(t)} \ldots + PSIS_{dis(t+x)}$

Figure 16 Pelvic Distance Travelled

Appendix A.4 Transfer Time – The number of frames collected during a task divided by 100 Hz equals the total transfer time in seconds

$$\text{Transfer Time} = \text{Frame}_x / 100$$

Figure 17 Transfer Time

Appendix A.5 Trunk Flexion Axis fixed to proximal vertebra and coincides with Z axis of proximal vertebra coordinate. In flexion, an individual bends their spine directly forwards relative their pelvis between 0 and 90 degrees. **Extension** refers to an individual bending their spinae from 0 to -90 degrees.

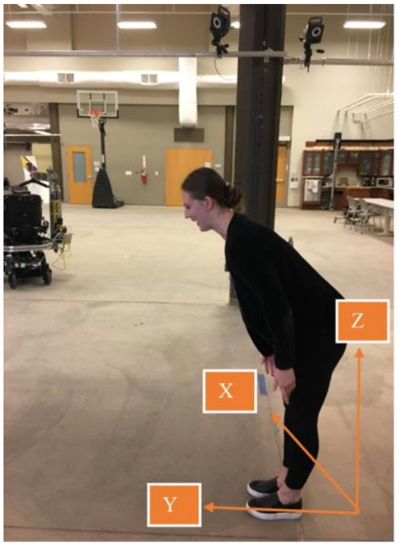


Figure 18 Trunk Flexion

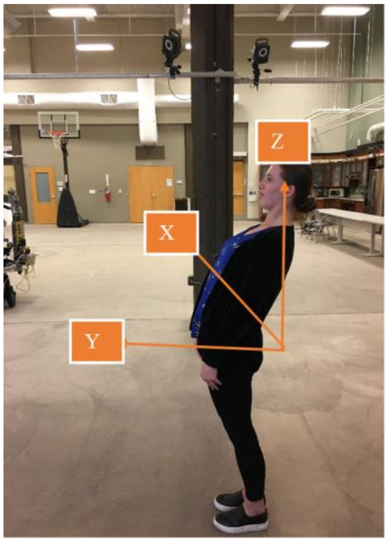


Figure 19 Trunk Extension

Appendix A.6 Axial Rotation: Axis filled to the distal vertebra and coincident with y axis of the distal vertabra coordinate system. In axial rotation, an individual twist their trunk either left or right along the Z axis.

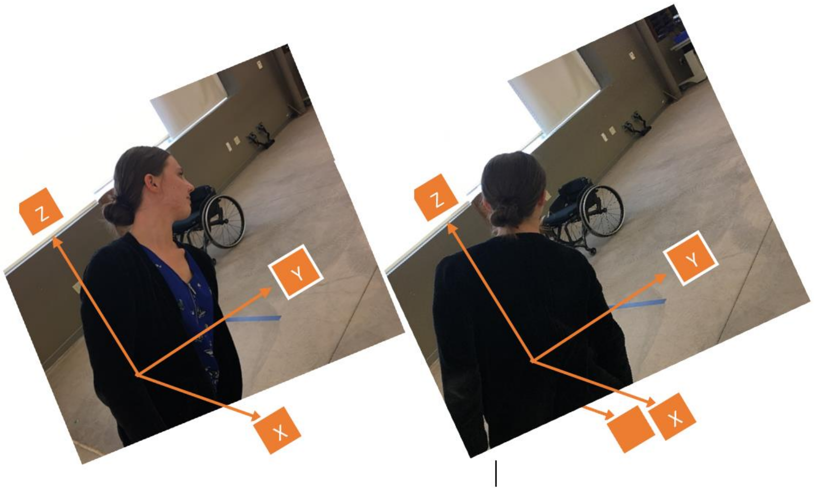


Figure 20 Axial Rotation

Appendix A.7 Lateral Bend: The floating/common axis perpendicular to e1 and e3. An individual bends their trunk relative to the X axis between -90 and 90 degrees

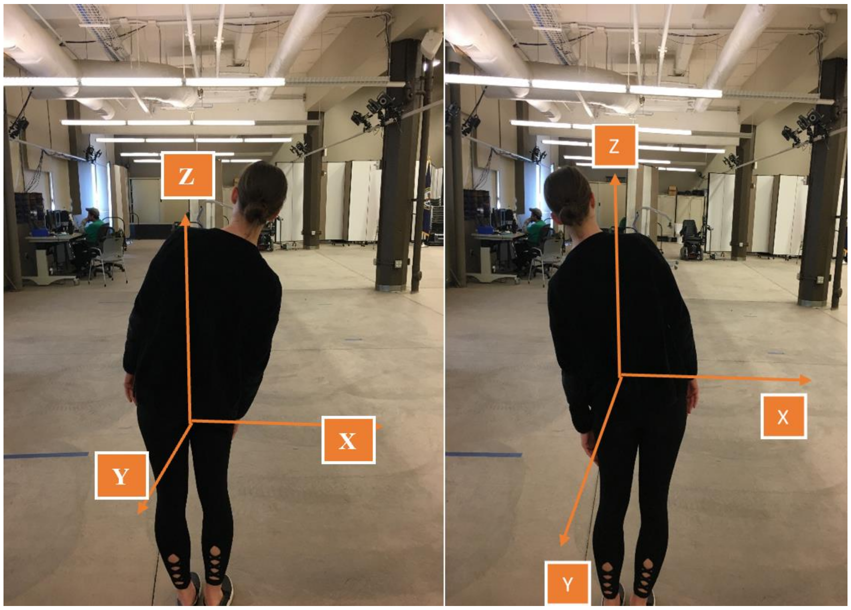


Figure 21 Lateral Bend

Appendix B Surface Electromyography Electrode Placement

Appendix B.1 Erector Spinae: The electrodes need to be placed at two finger width lateral from the proc. spin. of L1 (in line with bottom of the rib cage); Vertical Orientation

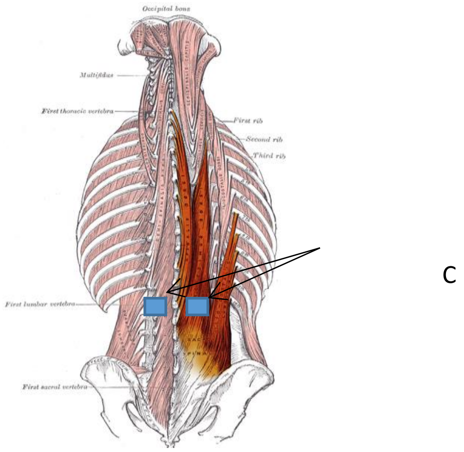


Figure 22 Erector Spinae Sensor Placement

Appendix B.2 Latissimus Dorsi: Place two electrodes two centimeters apart approximately four cm below the inferior tip of the scapula, half the distance between the spine and the lateral edge of the torso. Orientation should be slightly oblique angle of approximately 25 degrees.

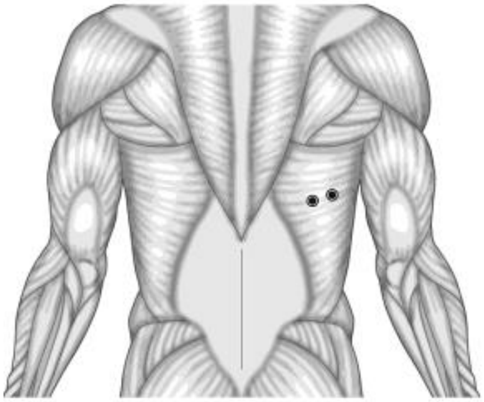


Figure 23 Latissimus Dorsi Sensor Placement

Appendix C Maximum Voluntary Contraction Exercises

The following provides an overview of the MVC exercises performed during manual muscle testing before the second study began. Information was used to compare dynamic trial information.

Appendix C.1 Erector Spinae: The subject lied on their stomach and arched their back up to the ceiling. Study personnel should hold the subject's legs down to ensure they do not come up of the mat. Resisting force may be supplied by study personnel at the shoulders, but should be administered with care

Figure 24 Erector Spinae Maximum Voluntary Contraction

Appendix C.2 Latissimus Dorsi: The subject lied on their stomach and internally rotated their arm, so that their thumb is facing the floor. The participant raised the rotated arm up and away from the table into extension. An investigator placed one hand on the opposite pelvis to stabilize the trunk. The study personnel may also apply a force to the forearm.

Figure 25 Latissimus Dorsi

Appendix D Phases a Transfer

It was important for us to identify the unique body mechanics occurring throughout the transfer. Using motion capture, empirical evidence, and video footage, investigators took note of three phases that occurred from one surface to another. These matched the transfer portion of patient handling and moving safety modules provided by the Federal Drug Administration. The specifics of each phase is labelled below.

Phase	**Start**	**End**
Lift	Caregiver first begins using the device	Caregiver lifts care recipient to maximum vertical height
Transport	Caregiver begins moving care recipient horizontally, adjusting lift appropriately	Care recipient is directly vertical to transfer destination
Placement	Caregiver lowers care recipient vertically onto transfer surface	Caregiver stops interacting with transfer device

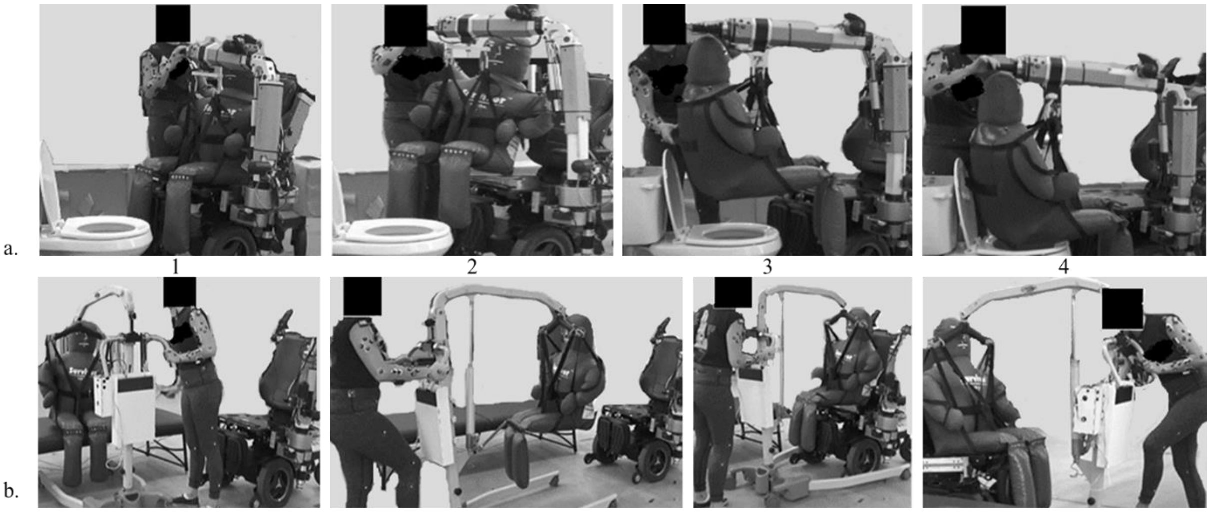
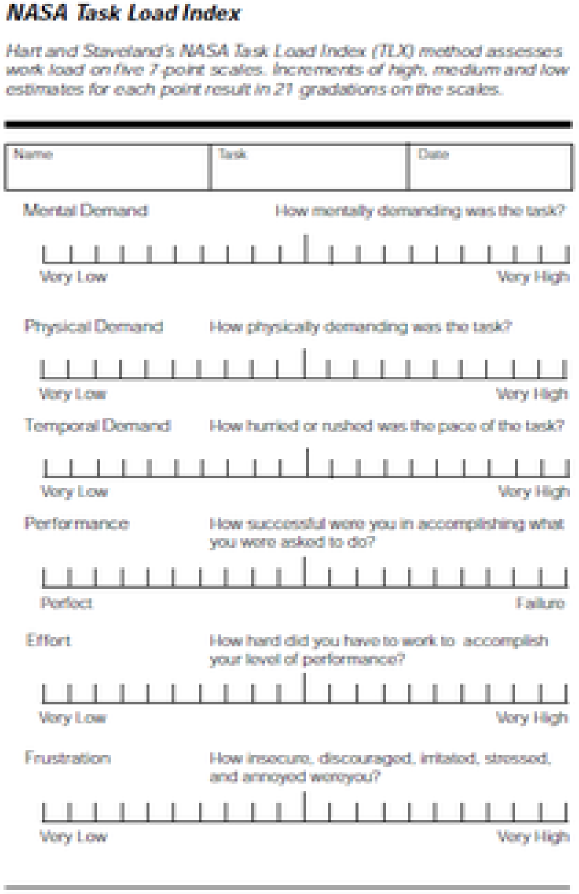


Figure 26 A Detailed Description of the Lift, Transport, and Placement Phases of a Caregiver Assisted Transfer Using Transfer Lifts

Appendix E Post Transfer Surveys

Appendix E.1 NASA-Task Load Index

Originally designed for pilots, the NASA-TLX is also applicable to human testing with novel clinical equipment. The two part survey includes a non-weighted portion which measures six common domains on a 0-100 scale (0=Success; 100=Failure): (1) Mental Demand, (2) Physical Demand, (3) Temporal Demand, (4) Performance, (5) Effort, and (6) Frustration. The scores collected from this portion are then weighted by a separate section in which the participant is asked to select between two domains what was a more meaningful domain in this trial. The raw scores are multiplied by the number of favored weighted answers and then divided by 15 for a weighted score. This improves off previous techniques because of the weighted aspect giving more meaning to the domains that impact successful completion of the experiment, though that portion does increase the risk for measurement error.



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 27 Raw Scale of the NASA-TLX Used in This Project

Appendix E.2 Usability Survey for Assistive Technology

A 10 cm visual analogue scale assessing multiple facets that impact successful completion of an assisted transfer using assisted devices. The survey is customized for address usability based on needs from both the caregiver and the care recipient perspective. Outcomes are measured on a scale of 0, indicating a more negative impact, to 10 cm, indicating a more positive impact. For instance, if a caregiver reported a reduced sense of fatigue using the RATD, that score would be marked close to “10” than to “0” while reporting ease also closer to “10” than to “0.” Two outcomes, back and shoulder pain included “Not a problem” check box, which was interpreted in this study as the maximum positive score (10).

Caregivers Only	**Care Recipients Only**	**Both Versions**
Back Pain	*Performance*	*Client Safety*
Shoulder Pain	*Comfort*	*Efficiency*
Fatigue	*Stability*	*Discomfort Frequency*
Caregiver Safety		*Discomfort Intensity*
Ease		*Appeal*

Figure 28 Outcomes Analyzed with the USAT (Both Caregivers and Care Recipient Versions)

Appendix F Interaction Effect Line Graphs

Appendix F.1 Phase I Angular Kinematics: Line graphs for range of flexion-extension, lateral bend, and axial rotation from Phase I

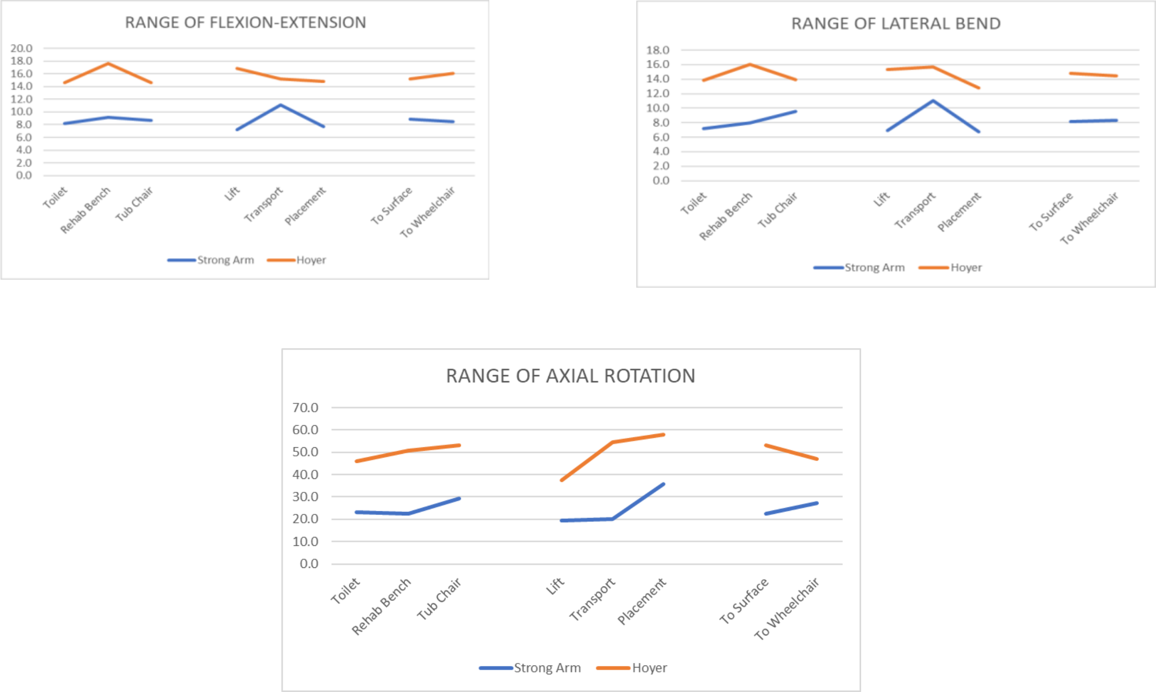


Figure 29 Phase I Angular Kinematics Interaction Effects

Appendix F.2 Phase I Linear Kinematics: Line graphs for pelvis adjusted distance travelled, instantaneous velocity, and acceleration

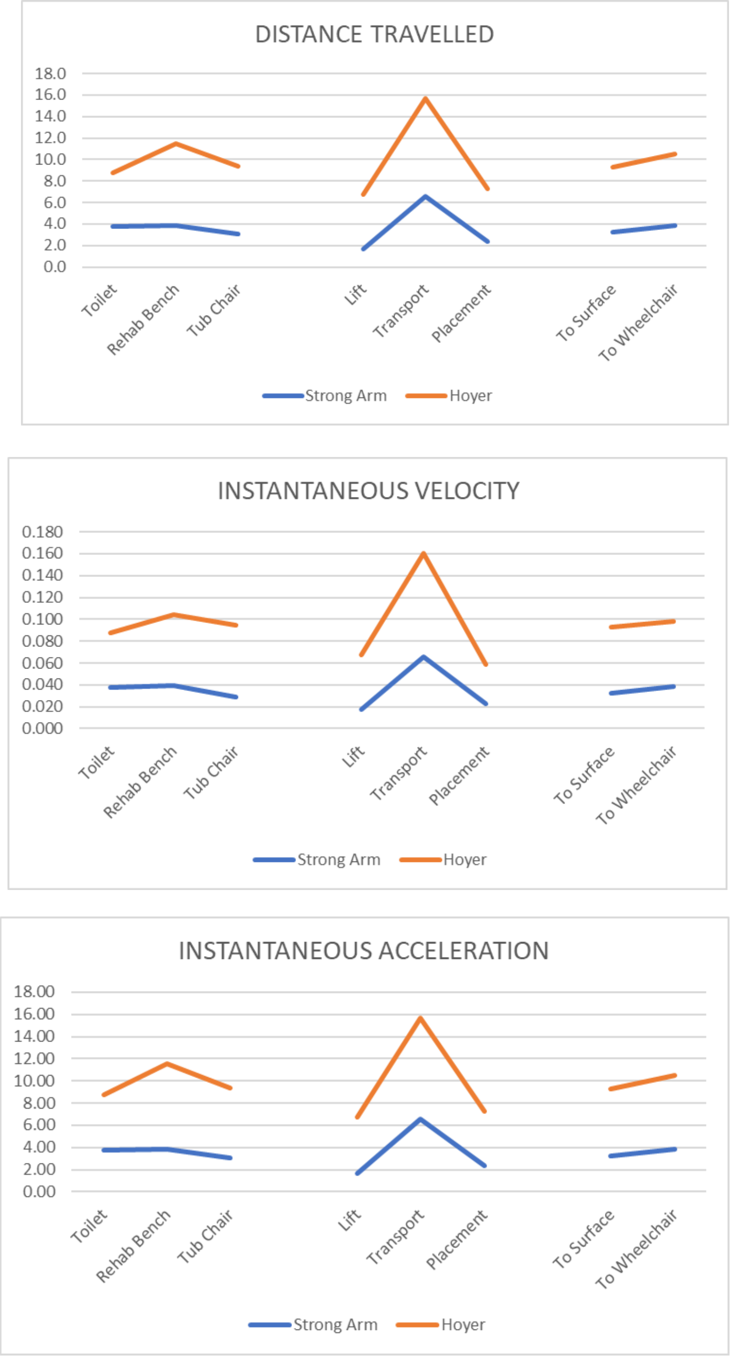


Figure 30 Phase I Linear Kinematics Interaction Effects

Appendix F.3 Phase I NASA-TLX: Task Load Demand Outcomes from Phase I

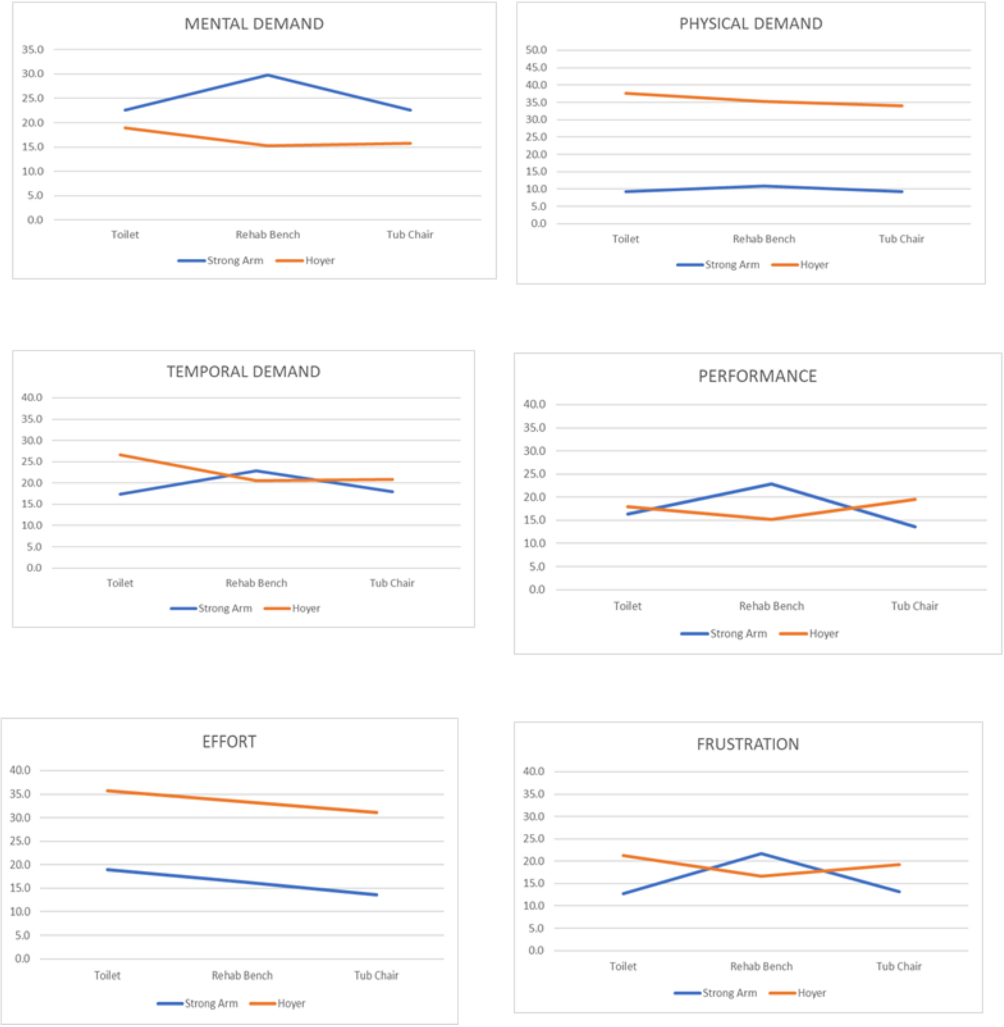


Figure 31 Phase I NASA-TLX Interaction Effects

Appendix F.4 Phase I Caregiver Usability: USAT Outcomes from Phase I

Figure 32 Phase I NASA-TLX Interaction Effects

Appendix F.5 Phase II Angular Kinematics: Range of flexion-extension, lateral bend, and axial rotation for Phase II

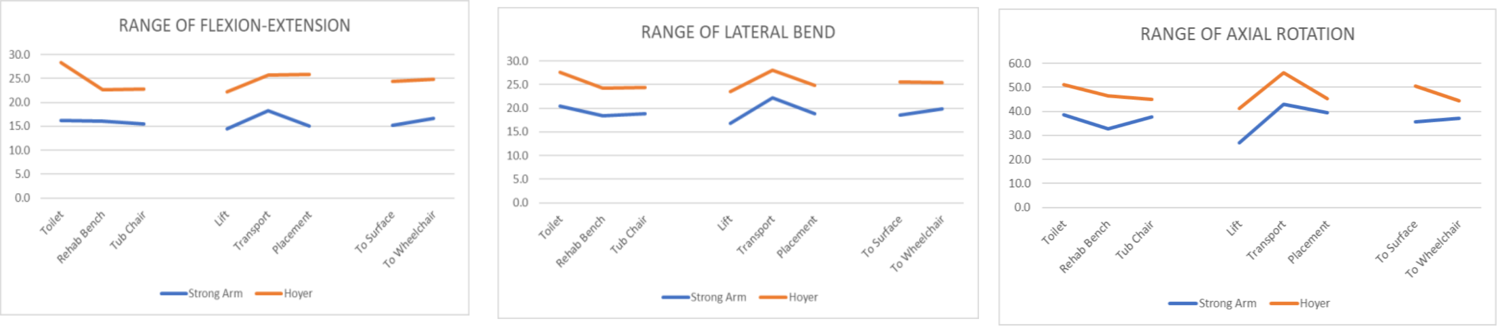


Figure 33 Phase II Angular Kinematics Interaction Effects

Appendix F.6 Phase II Linear Kinematics: Pelvic Adjusted Distance Travelled, Time, Instantaneous Velocity and Acceleration

Figure 34 Phase II Linear Kinematics Interaction Effects

Appendix F.7 Phase II Peak Percentage Maximum Voluntary Contraction: P%MVC for back, chest, and shoulder muscles

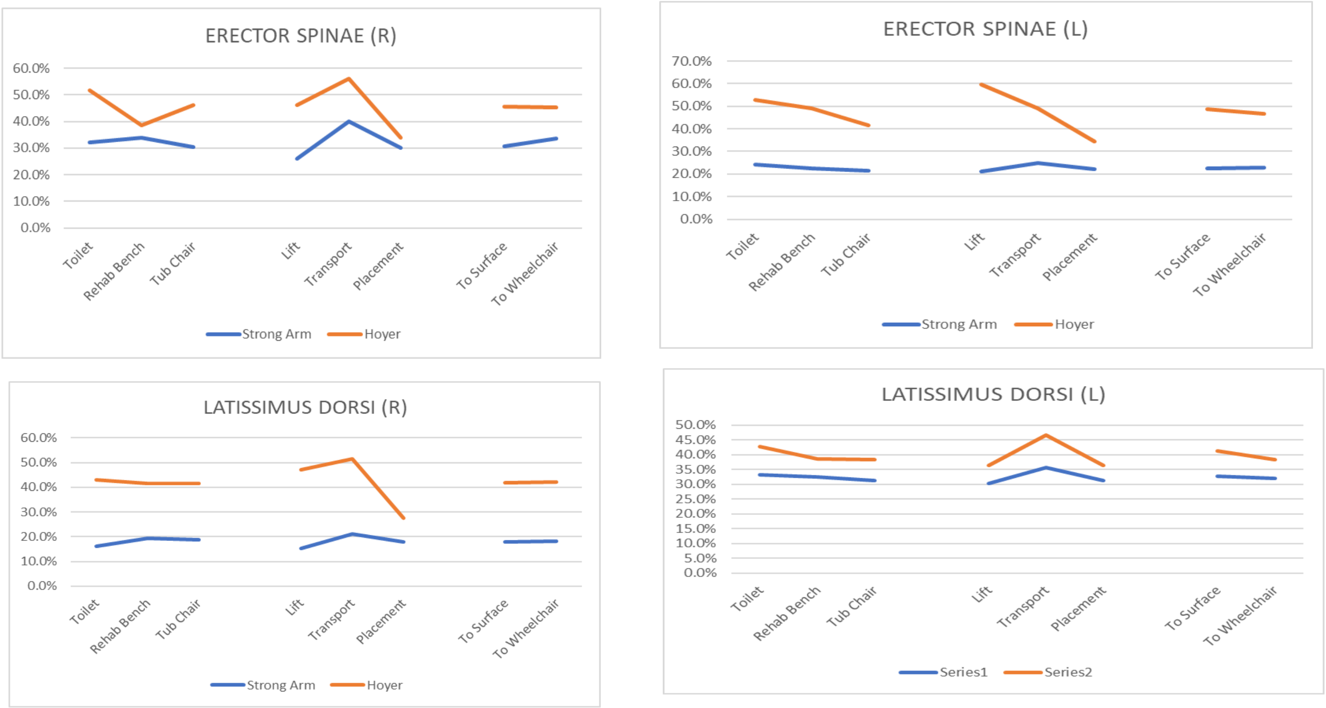


Figure 35 Phase II Peak Percentage MVC Interaction Effects

Appendix F.8 Phase II Integrated Maximum Voluntary Contraction: Integrated MVC for back, chest and shoulder muscles

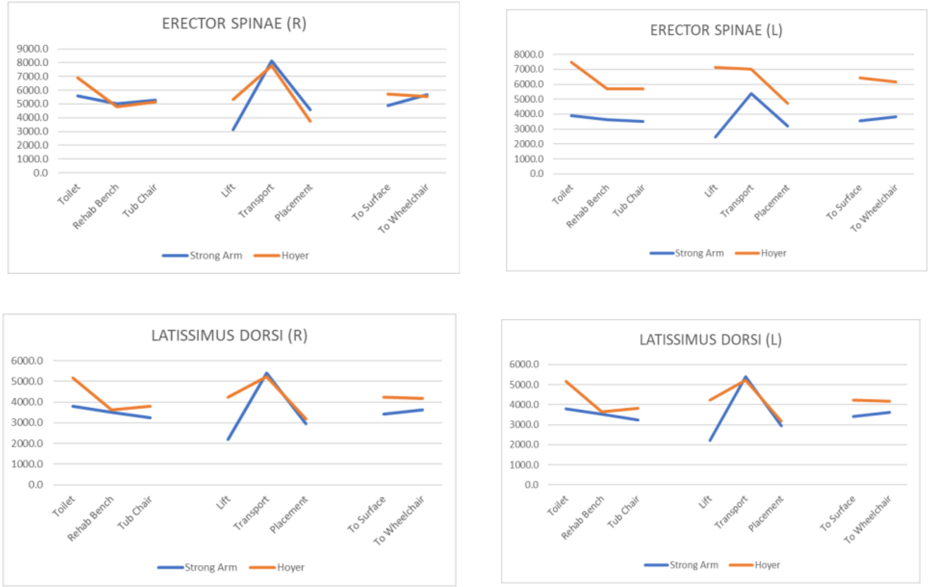


Figure 36 Phase II Integrated MVC Interaction Effects

Appendix F.9 Phase II NASA-TLX: Task Load Demand Load during Phase II

Figure 37 Phase II NASA-TLX Interaction Effects

Appendix F.10 Phase II Caregiver Usability: USAT outcomes from Caregivers

Figure 38 Phase II Caregiver Usability Interaction Effects

Appendix F.11 Phase II Care Recipient Usability: USAT outcomes from Care Recipients

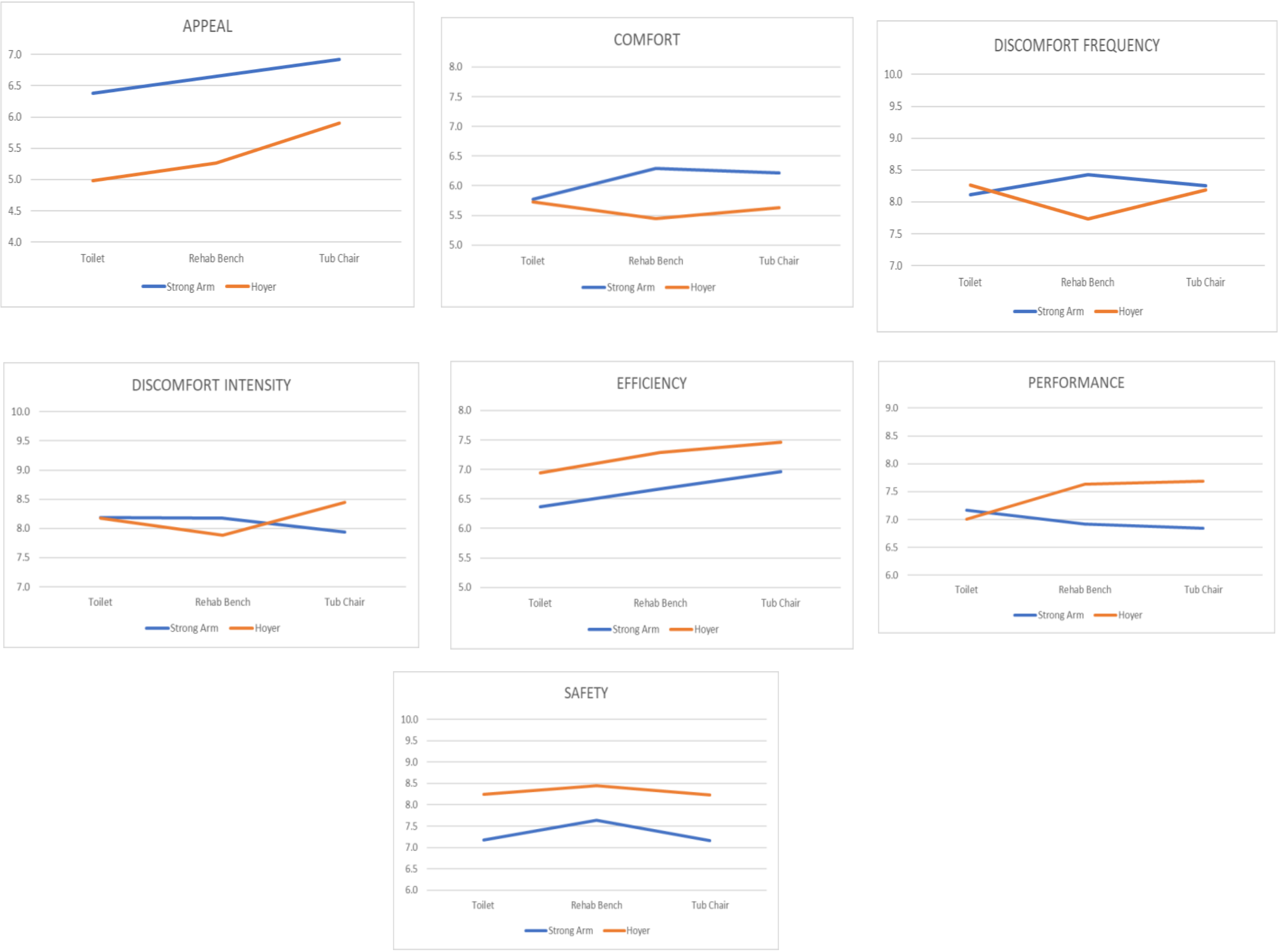


Figure 39 Phase II Care Recipient Usability Interaction Effects

Bibliography

1. Brault, W. "Americans With Disabilities: 2010 Household Economic Studies Current Population Reports." (2012).

2. Dicianno, Brad E., et al. "The voice of the consumer: a survey of veterans and other users of assistive technology." *Military medicine* 183.11-12 (2018): e518-e525.

3. Tsai, Chung-Ying, et al. "The relationship between independent transfer skills and upper limb kinetics in wheelchair users." *BioMed research international* 2014 (2014).

4. Jain, Nitin B., et al. "Association of shoulder pain with the use of mobility devices in persons with chronic spinal cord injury." *PM&R* 2.10 (2010): 896-900.

5. Xiang, Huiyun, A. M. Chany, and Gary A. Smith. "Wheelchair related injuries treated in US emergency departments." *Injury prevention* 12.1 (2006): 8-11.

6. Kirby, R. Lee, et al. "Extent to which caregivers enhance the wheelchair skills capacity and confidence of power wheelchair users: a cross-sectional study." *Archives of physical medicine and rehabilitation* 99.7 (2018): 1295-1302.

7. Sivaprakasam, Andrew, et al. "Innovation in transfer assist technologies for persons with severe disabilities and their caregivers." *IEEE Potentials* 36.1 (2017): 34-41.

8. Darragh, Amy R., et al. "Musculoskeletal discomfort, physical demand, and caregiving activities in informal caregivers." *Journal of Applied Gerontology* 34.6 (2015): 734-760.

9. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2015. *Bureau of Labor Statistics, U.S. Department of Labor*. 2016.

10. Statistics B. Incidence Rates for Nonfatal Occupational Injuries and Illnesses Inovling Days Away from Work per 10,000 full time workers by industry and selected events or exposures leading to injury or illness, private industry. United States Department of Labor. 2014.

11. Daraiseh, N. M., et al. "Low back symptoms among hospital nurses, associations to individual factors and pain in multiple body regions." *International Journal of Industrial Ergonomics* 40.1 (2010): 19-24.

12. Oranye, Nelson Ositadimma, et al. "Do personal factors or types of physical tasks predict workplace injury?." *Workplace health & safety* 64.4 (2016): 141-151.

13. Ribeiro, Tânia, Florentino Serranheira, and Helena Loureiro. "Work related musculoskeletal disorders in primary health care nurses." *Applied Nursing Research* 33 (2017): 72-77.

14. Waehrer, Geetha, J. Paul Leigh, and Ted R. Miller. "Costs of occupational injury and illness within the health services sector." *International Journal of Health Services* 35.2 (2005): 343-359.

15. Réminiac, François, et al. "Risks associated with obese patient handling in emergency prehospital care." *Prehospital Emergency Care* 18.4 (2014): 555-557.

16. ISO/TR 12296. Ergonomics — Manual handling of people in the healthcare sector. 2006

17. Waters, Thomas, et al. "NIOSH research efforts to prevent musculoskeletal disorders in the healthcare industry." *Orthopaedic Nursing* 25.6 (2006): 380-389.

18. National Alliance for Caregiving. "Caregiving in the US 2015." *NAC and the AARP Public Institute. Washington DC: Greenwald & Associates* (2015).

19. Reinhard, Susan C., et al. "Supporting family caregivers in providing care." *Patient safety and quality: An evidence-based handbook for nurses*. Agency for Healthcare Research and Quality (US), 2008.

20. Corrigan, Emily. "Fresh Perspectives on Safer Patient Lifting and Moving."

21. Nelson, Audrey, et al. "Technology to promote safe mobility in the elderly." *Nursing Clinics of North America* 39.3 (2004): 649-672.

22. Weiner, Chava, et al. "Repositioning a passive patient in bed: Choosing an ergonomically advantageous assistive device." *Applied ergonomics* 60 (2017): 22-29.

23. Dicianno, Brad E., et al. "The future of the provision process for mobility assistive technology: a survey of providers." *Disability and Rehabilitation: Assistive Technology* 14.4 (2019): 338-345.

24. Santaguida, Pasqualina L., et al. "Comparison of cumulative low back loads of caregivers when transferring patients using overhead and floor mechanical lifting devices." *Clinical Biomechanics* 20.9 (2005): 906-916.

25. Keir, Peter J., and Christopher W. MacDonell. "Muscle activity during patient transfers: a preliminary study on the influence of lift assists and experience." *Ergonomics* 47.3 (2004): 296-306.

26. Waters, Thomas R., et al. "Ergonomic assessment of floor-based and overhead lifts." *American journal of safe patient handling & movement* 2.4 (2012): 119.

27. Rice, Martin S., Sandra M. Woolley, and Thomas R. Waters. "Comparison of required operating forces between floor-based and overhead-mounted patient lifting devices." *Ergonomics* 52.1 (2009): 112-120.

28. Dutta, Tilak, et al. "A biomechanical assessment of floor and overhead lifts using one or two caregivers for patient transfers." *Applied ergonomics* 43.3 (2012): 521-531.

29. Lachance, Chantelle C., et al. "External hand forces exerted by long-term care staff to push floor-based lifts: Effects of flooring system and resident weight." *Human factors* 58.6 (2016): 927-943.

30. Grindle, Garrett G., et al. "Design and user evaluation of a wheelchair mounted robotic assisted transfer device." *BioMed research international* 2015 (2015).

31. Jeannis, Hervens, et al. "Initial development of direct interaction for a transfer robotic arm system for caregivers." *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2013.

32. Burkman, Jessica, et al. "Further development of a robotic-assisted transfer device." *Topics in spinal cord injury rehabilitation* 23.2 (2017): 140-146.

33. Sivakanthan, Sivashankar, et al. "Person transfer assist systems: a literature review." *Disability and Rehabilitation: Assistive Technology* (2019): 1-10.

34. Gerber, Linda M., et al. "Impact of falls on early mortality from severe traumatic brain injury." *Journal of trauma management & outcomes* 3.1 (2009): 9.

35. Alghadir, Ahmad, et al. "Work-related low back pain among physical therapists in Riyadh, Saudi Arabia." *Workplace health & safety* 65.8 (2017): 337-345.

36. Cimolin, Veronica, et al. "Spinal load in nurses during emergency lifting of obese patients: preliminary results." *La Medicina del lavoro* 107.5 (2016): 356-363.

37. Buchanan, Robert J., Chunfeng Huang, and Zhida Zheng. "Factors affecting employment among informal caregivers assisting people with multiple sclerosis." *International journal of MS care* 15.4 (2013): 203-210.

38. Maduri, Anupama, Bethany L. Pearson, and Sara E. Wilson. "Lumbar–pelvic range and coordination during lifting tasks." *Journal of Electromyography and Kinesiology* 18.5 (2008): 807-814.

39. Hodder, Joanne N., Michael WR Holmes, and Peter J. Keir. "Continuous assessment of work activities and posture in long-term care nurses." *Ergonomics* 53.9 (2010): 1097-1107.

40. Kromark, Kathrin, et al. "Back disorders and lumbar load in nursing staff in geriatric care: a comparison of home-based care and nursing homes." *Journal of Occupational Medicine and Toxicology* 4.1 (2009): 33.

41. Sadler, Sean G., et al. "Restriction in lateral bending range of motion, lumbar lordosis, and hamstring flexibility predicts the development of low back pain: a systematic review of prospective cohort studies." *BMC musculoskeletal disorders* 18.1 (2017): 179.

42. Jäger, Matthias, et al. "Lumbar-load analysis of manual patient-handling activities for biomechanical overload prevention among healthcare workers." *Annals of occupational hygiene* 57.4 (2013): 528-544.

43. Reinhard, Susan C., Carol Levine, and Sarah Samis. "Home alone: Family caregivers providing complex chronic care." (2012).

44. Davis, Kermit G., and Michael J. Jorgensen. "Biomechanical modeling for understanding of low back injuries: a systematic review." *Occupational Ergonomics* 5.1 (2005): 57-76.

45. Heydari, Abbas, et al. "EMG analysis of lumbar paraspinal muscles as a predictor of the risk of low-back pain." *European Spine Journal* 19.7 (2010): 1145-1152.

46. Rathore, M., et al. "A focused review–Thoracolumbar spine: Anatomy, biomechanics and clinical significance." *Indian Journal of Clinical Anatomy and Physiology Vol* 1.1 (2014).

47. Shojaei, Iman, et al. "Mechanical demands on the lower back in patients with non-chronic low back pain during a symmetric lowering and lifting task." *Journal of biomechanics* 70 (2018): 255-261.

48. Shin, J. Y., et al. "Underestimated caregiver burden by cancer patients and its association with quality of life, depression and anxiety among caregivers." *European journal of cancer care* 27.2 (2018): e12814.

49. Adelman, Ronald D., et al. "Caregiver burden: a clinical review." *Jama* 311.10 (2014): 1052-1060.

50. Hoonakker P, et al. MEASURING WORKLOAD OF ICU NURSES WITH A QUESTIONNAIRE SURVEY: THE NASA TASK LOAD INDEX (TLX). *IIE Trans Healthc Syst Eng*. (2011);1(2):131–143.

51. Miller, Aaron, et al. "Evaluation of the effectiveness of portable ceiling lifts in a new long-term care facility." *Applied ergonomics* 37.3 (2006): 377-385.

52. Krishnan, R. Hari, and S. Pugazhenthi. "Design and development of a robotic self-transfer device for wheelchair users." *Journal of Enabling Technologies* (2017).

53. Vinstrup, Jonas, et al. "Patient transfers and risk of back injury: protocol for a prospective cohort study with technical measurements of exposure." *JMIR research protocols* 6.11 (2017): e212.

54. Pompeii, Lisa A., et al. "Musculoskeletal injuries resulting from patient handling tasks among hospital workers." *American journal of industrial medicine* 52.7 (2009): 571-578.

55. Lidström, Helene, Magnus Lindskog-Wallander, and Eva Arnemo. "Using a Participatory Action Research Design to Develop an Application Together with Young Adults with Spina Bifida." AAATE Conf. 2015.

56. Wang, Hongwu, et al. "Stability analysis of electrical powered wheelchair-mounted robotic-assisted transfer device." *Journal of rehabilitation research and development* 51.5 (2014): 761-774.

57. Cooper, Rory A., Garrett G. Grindle, and Mark McCartney. "Robotic strong arm." U.S. Patent No. 9,254,234. 9 Feb. 2016.

58. Greenhalgh, Mark, et al. "Assessment of Usability and Task Load Demand Using a Robot-Assisted Transfer Device Compared With a Hoyer Advance for Dependent Wheelchair Transfers." *American journal of physical medicine & rehabilitation* 98.8 (2019): 729-734.

59. Blaauw ER, Greenhalgh M, Riemer V, Bass S, Kulich H, Grindle GG, Koontz AM, Cooper RA. Assessment of Muscle Activation of Caregivers Performing Dependent Transfers with a Novel Robotic Assisted Transfer Device Compared to the Hoyer Advance. *American Journal of Physical Medicine and Rehabilitation*. 2019. *(IN REVIEW)*

60. Crytzer, Theresa Marie, et al. "Identifying research needs for wheelchair transfers in the built environment." *Disability and Rehabilitation: Assistive Technology* 12.2 (2017): 121-127.

61. Dicianno, Brad E., et al. "Advancements in power wheelchair joystick technology: Effects of isometric joysticks and signal conditioning on driving performance." *American journal of physical medicine & rehabilitation* 85.8 (2006): 631-639.

62. Krishnan, R. Hari, and S. Pugazhenthi. "Design and development of a robotic self-transfer device for wheelchair users." *Journal of Enabling Technologies* (2017).

63. Joerns Healthcare. Hoyer® Advance. https://www.joerns.com/product/2473/Hoyer®-Advance.aspx. Accessed May 2, 2019.

64. Vaportzis, Eleftheria, Maria Giatsi Clausen, and Alan J. Gow. "Older adults perceptions of technology and barriers to interacting with tablet computers: a focus group study." *Frontiers in psychology* 8 (2017): 1687.

65. Fairbank, Jeremy CT, and Paul B. Pynsent. "The Oswestry disability index." *Spine* 25.22 (2000): 2940-2953.

66. Winwood, P. C., et al. "Development and validation of a scale to measure work-related fatigue and recovery: the Occupational Fatigue Exhaustion/Recovery Scale (OFER)." *Journal of Occupational and Environmental Medicine* 47.6 (2005): 594-606.

67. Kulich HR et al. "An ergonomic comparison of three different patient transport chairs in a simulated hospital environment." *Applied Ergonomics.* (2020). In press.

68. Wu, Ge, et al. "ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine." *Journal of biomechanics* 35.4 (2002): 543-548.

69. Desjardins P, Plamondon A, Gagnon M. Sensitivity analysis of segment models to estimate the net reaction moments at the L5/S1 joint in lifting. Medical and Engineering Physics, (1997): 20, 153-158.

70. ADA Standards for Acceptable Design. In: Justice USDo, ed201.

71. Patient Lifts Safety Guide. *Federal Drug Administration*

72. Hart, Sandra G., and Lowell E. Staveland. "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research." *Advances in psychology*. Vol. 52. North-Holland, 1988. 139-183.

73. Hart, Sandra G. "NASA-task load index (NASA-TLX); 20 years later." *Proceedings of the human factors and ergonomics society annual meeting*. Vol. 50. No. 9. Sage CA: Los Angeles, CA: Sage Publications, 2006.

74. Smolka, Jakub. "Efficiency of data interpolation methods." *Актуальні проблеми економіки* 12 (2013): 506-514.

75. Basmajian, John V. "Electromyography—dynamic gross anatomy: a review." *American Journal of Anatomy* 159.3 (1980): 245-260.

76. ABCs of Electromyography, 2006

77. Nelson, Audrey L., Ms Kathleen Motacki, and Nancy Menzel. The illustrated guide to safe patient handling and movement. Springer Publishing Company, 2009.

78. Koontz, Alicia M., Sarah R. Bass, and Hailee R. Kulich. "Accessibility facilitators and barriers affecting independent wheelchair transfers in the community." *Disability and Rehabilitation: Assistive Technology* (2020): 1-8.

79. National Alliance for Caregiving in collaboration with AARP. November 2009

80. National Alliance for Caregiving and the United Hospital Fund, Young Caregivers in the U.S., 2005

81. Rushton, Paula W., et al. "Understanding the burden experienced by caregivers of older adults who use a powered wheelchair: a cross-sectional study." *Gerontology and geriatric medicine* 3 (2017): 2333721417703736.

82. Adam, Alexander, Carlo J. De Luca, and Zeynep Erim. "Hand dominance and motor unit firing behavior." *Journal of neurophysiology* 80.3 (1998): 1373-1382.

83. Lee, Hyun, and Ji Heon Hong. "Comparison of trunk muscle activities in lifting and lowering tasks at various heights." *Journal of physical therapy science* 28.2 (2016): 585-588.

84. Field, Marilyn J., Alan M. Jette, and Institute of Medicine (US) Committee on Disability in America. "Coverage of Assistive Technologies and Personal Assistive Services." The Future of Disability in America. National Academies Press (US), 2007.Title Pag