CLASSIFICATION AND MODELING OF ACYCLIC STEPPING STRATEGIES USED DURING MANUAL MATERIAL HANDLING TRANSFER TASKS

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Industrial and Operations Engineering) in The University of Michigan 2008

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To Jenny
Acknowledgements

The process of getting a PhD was fun. Would I do it again? Did I know what I was getting into at the start? Did I know what I was doing all the time? Half the time? Was it easy? Would my wife let me do it again? The answer to all these questions is an emphatic No. But the process, as I now have the benefit of looking back on my 5+ year journey (in addition to having completed all the necessary requirements to become “Dr.” Dave), was fun. As I reflect on why I think the process was “fun” (you see, the fun is in quotes now, suggesting that maybe it wasn’t an ice cream and cake birthday party type of fun, but more of a getting hit in the head with a tack hammer kind of fun), I can only come up with one unifying entity that ties all the “fun” moments together. That one thing being the people who were a part of the process. A twist on the Ashanti proverb, “It takes a whole village to raise a child,” aptly describes my particularly fun process. For my experiences over the past 5 years, “It takes a whole village to write a PhD thesis,” seems the most appropriate. I would like to acknowledge (and in some special cases thank) my village.

It is not hard to begin, as there is one person, above all others, that has been at the center of my village since the beginning of my time in Michigan. She moved out to Ann Arbor one year after I arrived, supported me all the way through the process (even when she was in Berkeley, Ann Arbor, Chicago, Cape Cod, back to Chicago, again in Ann Arbor, and finally ending in Los Altos), and blessed me when she agreed to get married. Jenny has been my best friend, confidant, equal, and companion. Thank you Jenny for putting up with me and pushing me when I was down (in the good way…not the bad one). I never slept as well when you were away in another city. I don’t know if that was because I knew you wouldn’t be there to make me laugh in the morning, or give me a reassuring hug, or because I got so used to your knee being jammed in my back. I am sure it wasn’t the latter, although my low back pain did go away when you were gone (a coincidence I am sure). You were my constant supporter and champion. From making me leave work at work (so as not to drive us both crazy) to stocking the freezer with
home cooked meals right before you left Michigan for good. Without you being there, the process would have been considerably less fun (which it was when you weren’t living in Ann Arbor). As the dedication shows, this is for you (and for me too…but I think that is implied). Jenny, I love you.

The village would not be complete without my parents and brother. Mom and Dad, you set me up to make it through this process. You both instilled a solid work ethic (at least I think so), primarily by example, which I am proud to have. You taught me at a young age that work was not to be feared, just done. This philosophy helped me get through many long nights. It is too bad I could only visit during holidays, but I knew you both were only a phone call away and would always give me words of encouragement if I needed them. Mom, I probably missed the home cooked meals the most. No matter how hard I tried (and continue to try), I could never seem to replicate what you do. Dad, I think I recently realized why you pushed Chris and I so hard (and yelled at us so much). I could say it here, but then everyone would know. The important part is that I am beginning to appreciate and understand it. I can’t imagine a better two people to show me the way in the world and am thankful you both were always there for me.

My older brother Chris is also an integral part of the village. For all our lives, Chris has shown me the way by being the first one of us to try something new. In doing so, you were always looking out for me. From the time we were young when Dad strapped you to the back of his bike only to have your ankle get caught in the gears (now I know to hold my legs up if anyone ever puts me in a booster seat strapped on the back of a 10-speed) to getting your PhD a few years ago and sharing your experiences in the process. Even now as I am writing the acknowledgements, my recollections of your PhD thesis acknowledgements are guiding me. You only wrote one or two lines about me and I thought I got short changed. I didn’t want to make that same mistake you did to your brother, so I am giving you a whole paragraph. All kidding aside, thank you for always being there with an open ear and a willingness to help out your younger brother. It was great to have you and Monica in Ann Arbor during my last year and I appreciate the time we all got to spend together. I didn’t think we would ever live so close together again after we both left California and I am glad we got the chance before your time in England.
Perhaps the people that most shaped my time as a PhD student were the other students and friends I had the privilege of meeting. Thank you to my fellow PhD classmates including Kristi, Dave, Jinny, Mike L., Lisa, Sarah, Warren, Damon, Ken, Melinda, and Len who made those first few years a real special time. Dave Howland, you are one of a kind. I am truly lucky that we were able to be in so many classes and groups together that first year forcing us to get to know one another. Kristi and Mike, I look forward to spending time with both of you out in the Bay Area and continuing our friendship. Len, I hope you are doing well wherever you are. Thank you to my Ann Arbor Ultimate friends (Alex, Lisa, Brenda, and others) who kept me in shape and dragged me out when I might have wanted to just stay home.

My colleagues in the Human Motion Simulation (HUMOSIM) laboratory also deserve a large amount of credit for getting me through the PhD process. Woojin, you taught me the benefits of having more senior students help incoming ones. Matt Parkinson, you taught me how to live off the land and the value of mac and cheese and chili. Kevin, you taught me the importance of having fun and taking a break while working. You did not teach me how to play golf, which I am still regretting. In getting to know the other HUMOSIM PhD students (Clark, Heong-Jong, Divya, Josh, Deepti, Shaun), I truly learned a lot about myself and how a research laboratory should run. The work in this dissertation could not have been completed without the undergraduates that helped collect data, process motion capture files, and review plant video. Thank you Becky, Emily, Nuram, AJ, Sophia, Stefan, and Jen for all your hard work. The support of the HUMOSIM and Center for Ergonomics Staff was instrumental in setting up and conducting the primary laboratory experiment. Jim Foulke, your ideas were always novel and useful in solving any problem I brought your way. Chuck Woolley, I can’t thank you enough for constructing the electronic components necessary to make the experiment happen. Randy Rabourn, I really enjoyed our conversations at all the conferences we attended and your insights regarding the world. I also appreciate the help of Eyvind, Kara, and Rick for always putting in the time to get things done.

I was also very fortunate to share the fun PhD process with Suzanne Hoffman, who is going to defend her thesis in a few weeks. Suzanne and I had a similar philosophy regarding the PhD process and both treated being a graduate student as job. We would
arrive in the lab early in the morning and do our best to keep normal business hours. Suzanne was always willing to help me out with ideas or problems. Conservatively, I think we spent countless hours writing on the chalkboard (later converted to a whiteboard) trying to figure out a problem and what we were doing wrong. Suzanne pushed me (almost as much as Jenny) to finish. I am thankful that I had someone to share the process with and only hope I helped her half as much as she helped me. These words don’t express how much I appreciated (and how much it helped) sharing an office with Suzanne. Thanks again. I am looking forward to your defense and the time we can both be finished.

The section would also not be complete without acknowledging my dissertation committee, beginning with my co-chairs Matthew P. Reed and Don B. Chaffin. Don, your guidance and ability to see the big picture through all the small projects has helped define me as a researcher. Without your supervision, I am sure I would still be scoping and defining my PhD thesis. Matt, without your assistance, I don’t know if I would have finished. Your everlasting dedication to my PhD work and never ending exuberance for always being available to help me when an unsolvable problem crossed my path was truly inspiring. I can only hope that your first experience in chairing a PhD thesis taught you as much as I learned from being your student. James Ashton-Miller, your ideas on experimental design and how my work fits into the current literature forced me to describe my work with a refined clarity. Dan Ferris, your thoughts regarding the limitations and future applications of my work helped me identify how I would like to continue my career. Bernard Martin, your ideas regarding the theoretical implications of my work provided another way of interpreting and understanding future research.

Thank you again to all the people in my “village” that helped make this dissertation possible.
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Abstract

Foot placements are critical determinants of musculoskeletal loading in manual materials handling (MMH) tasks because of their effects on torso and upper-extremity posture. In spite of this importance, current ergonomic assessment tools lack valid models to predict the foot locations workers will chose. To address this need, a new comprehensive approach for modeling stepping behavior in MMH tasks was developed, based on field observations and a laboratory study. A method for qualitatively describing stepping strategies, the Lexical Transition Classification System (L-TRACS), was developed from observations of experienced operators performing MMH transfer tasks in an automotive assembly plant. Based on the field observations, the patterns of foot motions during object transfer tasks were hypothesized to be usefully described by a hybrid discrete/continuous model structure that predicts both strategies (behaviors) and the scaling of step placements within behaviors based on statistical analyses of laboratory data. A similar set of stepping behaviors was observed for both the laboratory and plant study. Contrary to expectations, approximately 70% of the object interactions (pickup or place operations) in both the plant and laboratory occurred with only one foot in contact with the ground. The four most frequently utilized strategies in the laboratory study accounted for 81% of the behaviors observed in the plant study. The results suggest that a majority of the stepping progressions used for MMH transfer tasks can be represented by a concise set of scalable behaviors. Based on the laboratory study, a Transition Stepping (TRANSIT) model was developed to predict foot placements for MMH tasks based on the task and operator characteristics. The model uses a new Quantitative Transition Classification System (Q-TRACS) that defines step placements during object pickups and deliveries. Multiple regression models were developed for five common stepping strategies. The placement and orientation of the terminal stance lead foot (i.e., the primary support foot) was predicted moderately well by subject and task attributes ($R^2$ of 0.69, 0.43, and 0.68 for lateral placement, fore-aft placement, and foot orientation,
respectively). Errors were typically less than one foot length. An Integrated Stepping Model (ISM) was developed that integrates the TRANSIT model with a model of gait using a flexible scaling structure to mediate between gait and transition stepping. The ISM uses the new concept of principal steps to smoothly join gait to transition stepping. The ISM is demonstrated using a range of work-cell scenarios with interspersed gait and acyclic stepping. The results of this research have direct application to ergonomic analysis of industrial tasks using digital human models, but also provide for the first time in the literature an integrated framework for representing both cyclic and acyclic stepping patterns with the quantitative detail required for biomechanical simulation and analysis.
CHAPTER 1

INTRODUCTION

1.1. Thesis Statement

Foot placements are critical determinants of musculoskeletal loading in manual materials handling tasks because of their effects on torso and upper-extremity posture. In spite of this importance, current ergonomic assessment tools lack valid models to predict the foot locations workers will chose. To address this need, a new comprehensive approach for modeling stepping behavior in manual materials handling tasks was developed, based on field observations and a laboratory study. A method for qualitatively describing stepping strategies, the Lexical Transition Classification System (L-TRACS), was developed from observations of experienced operators performing manual materials handling transfer tasks in an automotive assembly plant. Based on the field observations, the patterns of foot motions during object transfer tasks were hypothesized to be usefully described by a hybrid discrete/continuous model structure that predicts both strategies (behaviors) and the scaling of step placements within behaviors based on statistical analyses of laboratory data. This Transition Stepping (TRANSIT) model uses a new Quantitative Transition Classification System (Q-TRACS) that defines step placements during object pickups and deliveries using a novel parameterization that captures important effects of task variables. An Integrated Stepping Model (ISM) is proposed that integrates the TRANSIT model with a model of gait using a flexible scaling structure to mediate between gait and transition stepping. Gait can be readily represented under the Q-TRACS formulation, allowing the ISM to be considered as a general framework for representing foot placements for volitional tasks.
1.2. Theoretical Problem

Normal human locomotion, particularly cyclical gait, has been studied extensively. Research has examined the evolution of bipedal gait (Vaughan, 2003), quantified the kinematics of both normal and pathological gait (Oberg et al., 1993; Macellari et al., 1999; Perry, 1999), examined the effects of aging (Grieve et al., 1966; Dahlstedt, 1978; Owings et al., 2004; Richardson et al., 2005; DeMott et al., 2007), and investigated the effects of step variability (Stolze et al., 2000; Danion et al., 2003; Beauchet et al., 2005; Hausdorff, 2005), among other aspects. Reviews of the progression of gait research attribute its scientific beginning to work done by Borelli over 300 years ago in 1682 (Steindler, 1953). Since then, research on locomotion has expanded significantly (see Inman, 1981; and Whittle, 2002, for reviews). In fact, Vaughan (2003) reported that by 1999, there were over 7,000 published references on the biomechanics of human gait alone.

Acyclic aspects of walking have received much less attention. The postural adjustments and muscle activation patterns that induce a posterior shift in the center of pressure away from the stance limb during gait initiation from a quiet stance (Breniere and Do, 1981; Breniere and Do, 1986; Winter, 1995), and the characterization of the time necessary to achieve steady state walking from a quiet stance (Nissan et al., 1990; Breniere et al., 1991), have both been investigated. Gait termination has been sparsely studied (Winter 1995), although its importance with respect to age-related falls has been suggested (Sparrow et al., 2005).

Compensatory stepping, defined as the step(s) taken to maintain balance after a postural perturbation, is a type of acyclic stepping that has been examined in several studies. Interpretations of the use of compensatory stepping to maintain upright stance have evolved from being a strategy of last resort to one of functional importance (Maki et al., 1997). Maki et al. (1999) investigated the effects of speed and stability on the control of foot placement during compensatory stepping and found that stability was favored over speed as a control strategy of single-step reactions. Pai et al. (2002) compared static and dynamic model predictions at identifying the threshold for compensatory step initiation and found the dynamic model correctly predicted a step in 71% of the cases as compared to only 11% for the static model. The study of compensatory stepping
strategies has also provided insight toward the effects of age and balance impairment on maintaining upright stance (Schulz et al., 2005).

Turning is another aspect of locomotion that has received only modest attention, perhaps in part because the variability of the stepping patterns with which individuals can turn (i.e. one step, two steps, etc.) complicates efforts to develop a general understanding of turning. A justification for research on turning has been provided by Orendurff et al. (2006), who stated: “understanding the mechanisms of turning will provide insights driving design, therapy, and intervention to increase functional navigation in amputees, the elderly and individuals with neuromuscular pathologies.” Along these lines, research that has been conducted on two types of turns observed during locomotion (labeled as the “step turn” and “spin turn”) with respect to the relative stability provided by each strategy (Hase and Stein, 1999; Taylor et al., 2005). The study of turning strategies observed during specific tasks, such as turning while picking up an object, has provided unique insight toward the effect of age on functional turning kinematics (Meinhart-Shibata et al., 2005).

The stepping behaviors associated with turning, and particularly those related to the actions taken during manual materials handling, are also of greater interest for ergonomics analysis than cyclical gait. Twenty percent of all steps taken by the general population involve turns (Sedgeman, 1994) and the actual percentage of steps involved in turns when in a constrained environment, such as an industrial work cell, may be higher. Moreover, the time periods during an industrial workers’ job cycle that are of greatest interest to the ergonomist are often those in which a load is picked up or placed, actions that are often accompanied by acyclic steps. The worker may also be at higher risk for injury when turning than when walking. Individuals who fall during a turn, as opposed to a fall during linear walking, are eight times more likely to experience a hip fracture (Cumming and Klineberg, 1994).

**Technical Basis for Research Involving Out-of-Plane Stepping**

Perhaps when Steindler (1953) acknowledged the growing field of locomotion in a review of gait research up to that point, he did not realize his insight would remain applicable over fifty years later. Steindler wrote:
“To judge from the literature there is every indication that the interest which the profession shows in the mechanics of human gait is on the increase. This is directly attributable to the considerable advances which have been made in the study of locomotion…”

Although Steindler was surely talking about the improvements in research technology of the day, his reasoning is also applicable to the recent increase in attention to acyclic bipedal motion. In particular, two technological improvements are not only advancements in the methods with which human movement can be studied and represented, but also are driving the need for its research:

1. The capability for recording human performance to include three-dimensional motion (Sturman, 1994; Sutherland, 2002) and forces (Sutherland, 2005); and
2. The capacity to display and simulate human movements in realistic three-dimensional computer simulations.

Three-dimensional motion capture systems are now the standard approach for studying human motions (compared with planar movie and video systems from previous decades). More importantly for the current work, rapid advancements in computer graphics capability have led to the widespread adoption of digital human figure models for ergonomic assessment and computer-aided design.

1.3. Applied Motivation

Digital human figure models (DHM) are used for a variety of applications spanning job safety evaluation (including biomechanical, postural, and strength analysis), reach/space accommodation, vision capability and occlusion, and task visualization. Accurate assessment of operator job safety and performance is an important component of efforts to reduce worker injuries and the associated costs. The U.S. Bureau of Labor and Statistics (BLS) reported in 2004 that 5.1 million workers were classified under ‘Manual Moving Occupations’ (BLS 2006-2007) and reported 173,400 cases (19.5 reported incidences per 10,000 full-time workers) of acute overexertion solely due to lifting. The National Research Council in the United States presented conservative estimates of costs (defined by compensation, lost wages, and lost productivity) in 1999 associated with musculoskeletal disorders to be between $45 and $54 billion annually. Stewart et al. (2003) reported a value of $31.4 billion dollars in 2002 of total productive
time lost due to back or unspecified musculoskeletal pain from a random sampling of 28,902 working adults. Even under the most ideal conditions, the use of digital human models could not eliminate all the cases of overexertion and costs associated with musculoskeletal pain reported above. Nonetheless, proactive ergonomics has tremendous potential to improve the design of work and reduce the risk to workers (Chaffin, 2005). Injuries can be prevented by identifying and addressing potentially hazardous tasks before workers are exposed.

**Need for Valid Step Prediction in Virtual Design**

The evolving field of proactive ergonomics as an engineering discipline (Chaffin, 2005) is driving the necessity for accurate simulation of human movement. Proactive ergonomics is following the trend of other engineering disciplines and is quickly transitioning into the extensive use of virtual environments as a context for design decisions. Virtual environments are preferred to physical prototypes for their reduced cost and for their potential to reduce the time necessary to conduct a particular analysis from which an engineering decision will be based. An essential tool for proactive ergonomics is the digital human model (DHM), a software representation of the human form. As with other engineering software, the success of DHM technology is dependent on the accuracy and ease of use of the tools. For example, finite element modeling of material stresses has developed into a quantitative discipline that is accepted as a proven tool for virtual testing. Human figure models have not achieved that same level of acceptance due to their substantial shortcomings in representing the relevant complexities of the human body and, particularly, human behavior.

Current figure models provide only modest behavior simulation capability, and most posture input relies on the analyst. The most common method for defining the figure posture is through manual manipulation, in which the ergonomist assumes the role of the animator. The analyst manually postures the manikin performing a particular task, usually based on previous observations, personal experience, and intuition.

Video analysis and motion capture technology has been widely used to obtain postures for use in figure model software for static and dynamic analysis, but this approach presumes that a worker or at least a participant in a mockup study has performed the task. Replication of 3D postures from a single source (i.e. video recording)
has been shown to be consistent across multiple experts (Sullivan et al., 2002), but Burt et al. (1999) reported a significant range of inter-observer agreements from 26% for right shoulder elevation to 99% for left wrist flexion depending on the angle being observed. Motion capture hardware can be used to obtain worker postures, but the methods can be cumbersome, time-consuming, and expensive. Moreover, the use of data from a single person performing the job may not reveal hazards that would be encountered by an individual of a different body type or size (Godin et al., 2006). Perhaps most importantly, the time and financial resources to build a mockup and record posture data are often not available.

For many situations in which DHMs are used for design purposes, no standardized methods are available to guide the posturing of the manikin. Consequently, the reproducibility of analyses across operators, and even the within-operator repeatability, are poor. The lack of rigor in the critical determination of task postures undermines the credibility of DHM analyses as a part of engineering practice. Rigorous, robust, well-validated methods for predicting postures and motions are needed.

For DHMs (as applied to ergonomics) to be accepted as a recognized engineering tool, the results from the flow of information depicted in Figure 1.1 must produce both repeatable and reproducible results for the majority of analyses across similar input conditions. The current impediment in generating reproducible results lies largely in being able to consistently simulate the posture or motion of the figure model. Two potential methodologies that attempt to address the issue of reproducible posture selection are standardized usage procedures for human models and improvement of the motion prediction algorithms used to simulate human postures. Although standardized procedures would reduce the variability in results for some well-defined task analyses (e.g., normal driving posture), this approach does not seem to have much potential for improving cross-operator reproducibility for more complex or less-constrained tasks. Moreover, it does not address the critical issue of accuracy. Standardizing on inaccurate methods might not constitute much progress.

In this context, accurate prediction of foot placements is a crucial enabler for whole-body posture and motion simulation. For many tasks, the job requirements constrain the hand(s) and gaze of the human operator to a part or object providing a
certain amount of constraint to the possible number of feasible postures. Unfortunately, the feet are not as constrained by task conditions, which significantly contributes to the variability and lack of reproducibility between different analysts when defining these postures. Consequently, this dissertation focuses on the development of methods to predict a critical aspect of human behavior (foot placements) for use in ergonomic analyses using human figure models.

Figure 1.1. Information flow for a representative ergonomic evaluation that utilizes a digital human figure model.

Why Study Stepping Motions? The Manual Materials Handling Problem

The step placement and timing problem is a component of the more general problem of predicting postures and motions for work tasks. Several predictive models have been developed to generate postures for manual material handling tasks (Andres, 1991; Ayoub et al., 1995; Ayoub, 1998; Dysart et al., 1996; Perez, 2005). Unfortunately, these static and dynamic predictive lifting models require as input an initial posture or other postural constraints, such as pre-determined foot placements. No lifting models are known to have the capability to predict the unconstrained initial posture, as well as the lifting or transfer motions a worker would use. However, several biomechanical models are currently available that can be used to assess operator safety based on different body and tissue stress criterion (3DSSPP; Chaffin et al., 1970; Ayoub et al., 1995; Ayoub, 1998; Dysart et al., 1996; Perez, 2005), but these models require worker posture or
motion as an input. The accuracy of the input posture (and motion) is critical for realistic estimates of internal body stresses when using such models. Small errors in human motion kinematics can result in large errors in joint moments and forces (Holden et al., 1997; Reinbolt et al., 2007). In particular, foot placements have been shown to strongly affect the ensuing posture and motion, and subsequently affect the stresses on the low back and other body regions that are being analyzed (Kingma et al., 2004; Wagner et al., 2005; Plamondon et al., 2006).

Many experimental investigations into lifting limits, best practices, and behaviors have focused on sagittal plane lifting, and to a lesser extent asymmetric lifts that require no foot movements (Chaffin et al., 1970; Martin et al., 1972; NIOSH, 1981; Health and Safety Commission, 1982, 1992; Troup et al., 1983; Waters, 1993; 3DSSPP, 2002). However, in a study by Baril-Gingras et al. (1995) that focused on the handling strategies of objects other than boxes in a distribution center for a large transport company, 57% of the 944 handlings that were catalogued consisted of workers taking two or more steps. Furthermore, approximately 77% of the observed efforts documented by Baril-Gingras et al. (1995) included some type of horizontal component to the effort, as opposed to a strictly vertical exertion or sagittal plane lift. Although only from a single study, the observation that 4 out of every 5 observed efforts were not sagittal plane but asymmetric lifts, and over half of the object transfers required two or more steps, is not reflected in the current lifting analysis (or motion prediction) methods.

During manual materials handling tasks, particularly those in work cell environments, steps (foot placements) facilitate two primary objectives of human movement: progression and orientation. The progression objective is associated with work cell tasks that can be described by verbs such as ‘walk’ or ‘carry,’ where the primary intent of movement (particularly the lower extremities) is to translate the body to a new position. The orientation objective is associated with tasks that are described by verbs such as ‘lift’, ‘push’, or ‘pull’, where the primary intent of the movement is to orient the body, usually to then be able to perform a secondary task with the hands, or to better visualize an object. Although progression steps are necessary for bipedal motion and may affect the selection and placement of configuration steps, they are not traditionally associated with postures of ergonomic interest (i.e. extreme and/or terminal
postures). However, orientation steps are more relevant to current ergonomic assessment tools (like the biomechanical models listed above) where knowledge of such steps are required when defining the posture during an exertion that would then be used as input for postural analysis.

**Step Prediction in DHMs**

The application of motion prediction in DHM software to address the need for adequate step predictions presents a set of requirements spanning qualitative aesthetics and quantitative realism of motions (Lockett et al., 2005; Reed et al., 2005) (Figure 1.2). With respect to DHMs and ergonomics, the current posture and motion prediction models for the lower extremities fail in two general ways. First, no general-purpose model is available to predict the lower extremity configuration of an operator performing manual material-handling tasks while standing. Second, DHMs lack the ability to realistically simulate stepping motions beyond a very small number of specific scenarios (i.e., cyclical gait and running). As previously mentioned, current implementations of commercial DHM software address this issue by requiring the user to create specific stepping behaviors. This is traditionally accomplished through animation and key-framing techniques. In addition, in the few situations where there exist predefined models that can be used to simulate bipedal gait, the transitions to and from a locomotive state are still poorly defined. In particular, the initiation, termination, and transitions between a locomotive and novel task specific stepping states usually result in kinematically infeasible motions, with glaring discrepancies between the simulated and physically plausible motion (Badler, 1993).
Figure 1.2. Select requirements for utilizing motion prediction algorithms with ergonomic assessment tools.

**Model Concept**

The prediction of the stepping pattern, stance, and foot placements used during bipedal motion can be used to drive the feet of a human figure model for use with ergonomic analysis, and thus address the lack of posture prediction methods for the lower extremities set forth in the previous paragraphs (Reed et al. 2006). These constraints may also be helpful for better defining realistic motions or postures, and help improve not only the visual clarity of simulated bipedal motion, but also advance the understanding of how we move when planning and executing novel stepping patterns in a constrained environment. An industrial work cell environment, where a variety of manual materials handling tasks are routinely performed, is used as a paradigm environment to help define potential requirements necessary within a robust stepping model. Work cell environments, particularly ones in which MMH tasks are performed, have been previously observed to contain not only a variety of tasks of ergonomic interest (i.e. pickup, delivery, carry, walk, etc.), but additionally a variety of lower extremity postures/motions used by the operators to accomplish those tasks within the relatively small work area (Drury et al., 1982; Kuorinka et al., 1994; Baril-Gingras et al., 1995; Lortie et al., 1996). In addition, the hope is that the capability to simulate many of the
tasks that are observed in an industrial work cell will be applicable to other applications where individuals perform similar tasks as those described above.

**Proposed Method**

Figure 1.3 is a schematic of a hypothesized step prediction process, where the output could potentially be used as input to whole body motion prediction models. A task representation consisting of a sequence of events that each correspond to a unique step prediction model is required. Additionally, a representation of the environment and human figure are also necessary. For each action in the task list, a model to predict the spatial aspects of the feet end-effectors to perform that action is selected. Finally, an integrator combines the individual model predictions into a coordinated stepping motion.

Figure 1.3. Hypothetical modeling structure used to parameterize the spatiotemporal constraints of the lower extremity end-effectors

The advantage of decoupling the goal(s) of the movement from the method used to fully prescribe the lower extremity motion is in the flexibility of available modeling methods with which to realize the complete motion. A potential disadvantage of separating the parameterization of the goal movement with the method to synthesize the lower extremity (or whole body motion) is that if the parameterization is not prescribed but modeled in itself, there exists the potential for inaccuracies in end-effector prediction, which could lead to kinematically infeasible postures or motions. An example of this type of discrepancy with respect to gait modeling would occur if a step length were prescribed that was kinematically impossible, or if a walking velocity were prescribed that was physically unrealistic. Similar methods for defining the goal states of the hand end-effector(s) have been shown to have success for simulating reaching motions with the upper extremities (Faraway 2003). Algorithms of this type have been integrated into
a variety of whole body models used for ergonomic assessments including the Human Model Testbed (Badler et al. 2005), and the HUMOSIM Ergonomics Framework (Reed et al., 2006). More specifically, Badler et al. (2005) describes an approach for simulating human movement using footprints defined as points along a B-Spline trajectory, and using those footprints as constraints for biped motion.

The output of the step parameterization prediction process proposed in this thesis has the potential to be immediately useful for such applications as improving the estimates of ambulation time necessary to perform a job, or potentially quantifying the necessary floor area required for a single or multiple operators maneuvering within a work cell. If successfully incorporated into a whole-body motion simulation framework, the process proposed here could potentially have a profound impact in furthering the understanding of the motivations and tradeoffs of out of plane non-cyclic stepping motions with respect to the biomechanical measures of balance, joint stress, muscle force, and muscle activation where current models have had limited utility.

1.4. Research Objectives

There are four principal objectives of this research:

1. Develop a method for representing and classifying the stepping patterns frequently observed during manual material handling lifting transfer tasks, and present the frequency and distribution of transfer tasks conditions, and the associated stepping patterns within an industrial setting.

2. Investigate the effects of anthropometric variables and task conditions, consisting of the lifting hand(s), object height, object weight, approach angle, departure angle, and turn angle on step pattern selection and foot position(s), with respect to object location during manual material handling lifting tasks.

3. Develop and empirically evaluate foot placement prediction models from laboratory data for commonly observed manual material handling transfer stepping patterns.

4. Develop a framework for integrating cyclical and non-cyclical foot placements in the ground plane within a digital human modeling platform.
1.5. Thesis Organization

The body of this thesis consists the following four chapters, each directly addressing one or more of the research objectives.

Chapter 2 proposes a classification taxonomy and nomenclature for identifying and grouping the acyclic stepping patterns observed during manual material handling pickup and delivery tasks. The Lexical Transition Classification System (L-TRACS) defines stepping behaviors associated with turns during pickups and deliveries by categorizing the associated steps. The classification scheme is applied to 42 jobs that yielded 529 uniquely performed pickup and delivery transfer tasks from an automotive assembly plant. Summary statistics regarding task conditions in addition to the observed stepping patterns are presented.

Chapter 3 describes a laboratory experiment wherein the motions of 16 participants were recorded while performing a variety of pickup and delivery transfer tasks. Task and anthropometric factors that significantly affected stepping pattern selection and foot placement are reviewed.

Chapter 4 presents the development of the Transition Stepping (TRANSIT) model, a new quantitative model for predicting stepping behaviors for manual materials handling tasks. A new parameterization of step timing and placement is introduced. The Quantitative Transition Classification System (Q-TRACS) describes predicting step placement using coordinate systems that take into account important task effects. Linear regression models for five commonly observed stepping behaviors used to perform manual material handling transfer tasks based on the laboratory study and results presented in Chapter 3 are presented. A multinomial logistic regression model is constructed for selecting a stepping behavior from those classified using the nomenclature defined in Chapter 2. Five stepping behaviors are examined based on the results from Chapter 2 in which the five most frequently observed stepping patterns accounted for over 80% of all observations.

Chapter 5 presents the Integrated Stepping Model, a new approach to simulating step placements for gait and acyclic stepping. The ISM draws on the parameterization developed in Chapters 2 and 3, and integrates the TRANSIT model developed in Chapter 4 with a gait model based on the Q-TRACS parameterization. The ISM presents a
method for integrating step placements predictions from individual models for use independently or as potentially imposed end-effector constraints for whole body stepping models. An implementation of the modeling structure is presented for integrating a gait model derived from the literature and the TRANSIT (Transition Stepping) model developed for predicting the foot placements used during manual material handling transfer tasks (Chapter 4).
1.6. References

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CHAPTER 2

A NEW FOOT MOTION CLASSIFICATION METHOD FOR MANUAL MATERIAL HANDLING TRANSFER TASKS APPLIED TO AN AUTOMOTIVE ASSEMBLY PLANT

2.1. Abstract

Ergonomic job analysis commonly applies static postural and biomechanical analysis tools to particular postures observed during manual material handling (MMH) tasks, usually focusing on the most extreme postures or those involving the highest loads. When these analyses are conducted prospectively using digital human models, accurate prediction of the foot placements is critical to realistic postural analyses. In automotive assembly jobs, workers frequently take several steps between task elements, for example picking up a part at one location and moving to another location to place it on the vehicle. A detailed understanding of the influence of task type and task sequence on the stepping pattern is necessary to accurately predict the foot placements associated with MMH tasks. The current study examined the patterns of foot motions observed during automotive assembly tasks. Video data for 529 pickup and delivery tasks from 32 automotive assembly jobs were analyzed. A minimum of five cycles was analyzed for each task. The approach angle, departure angle, hand(s) used, manipulation height, and the patterns of foot steps were coded from the video. Object weight was identified from the job information sheet provided by the assembly plant. Three independent raters coded each video and demonstrated an intraclass correlation coefficient of 0.54 for identification of the terminal stance type. Based on an analysis of the distribution of stepping behaviors during object transitions (pickups or deliveries), a Transition Classification System (TRACS) was developed. TRACS uses a compact notation to quantify the sequence of steps associated with a MMH transition. Five TRACS behavior groups accounted for
over 90 percent of the transition stepping behaviors observed in the assembly plant. The results from this paper provides a classification scheme useful to a predictive model for selecting a transition stepping behavior, and how such a model can be constituted to facilitate accurate, prospective ergonomic analyses.

2.2. Introduction

Many Manual Materials Handling (MMH) jobs require an operator to perform a variety of standing work (SW) tasks. Standing work can be further partitioned into stationary standing work (SSW), in which the operator can primarily stay in one location, and non-stationary standing work (NSSW) in which the operator is required to move about a work area, usually by walking or acyclic stepping. Baril-Gingras et al. (1995) analyzed 944 manual material handling events in a large transport company. In over half (57%) of the recorded object transfers, the worker took two or more steps. Approximately three-quarters of those 944 jobs (77%) included a horizontal component to the lift (i.e. out of the sagittal plane). Cumming and Klineberg (1994) reported that injuries related to a fall are eight times more likely to result in a fracture if the fall occurs during a turn versus straight line walking, suggesting that turns should be a particular focus of ergonomic analysis. Among MMH tasks, lifting in SSW has received special attention over other tasks because of its prevalence in job sites across industries and association with injury (Bendix et al., 1983; Gagnon et al., 1993; Burgess-Limerick et al., 1998; Dysart et al., 1996; Kollmitzer et al., 2002). Lifting in conjunction with NSSW has received comparatively little attention.

Tasks that are already being performed by workers are often assessed through postural and biomechanical analyses based on photographs or videos of people performing the task. However, when a new job is being designed, digital human figure models are now commonly used to simulate the workers (Chaffin, 2005). The accuracy of these analyses is dependent on accurate prediction of postures and motions, including foot placements.

The goal of the current work is to quantify the patterns of foot motions for MMH tasks in automotive assembly, particularly those associated with NSSW. Methods for quantifying and comparing physical task performance vary depending on the required level of precision. For kinematic comparisons, qualitative behavior strategy descriptions
(Delisle et al., 1999; Hase et al., 1999), quantitative joint angle position, velocity and acceleration profiles (Winter 1995), and various postural rating schemes (Karhu et al., 1977; Corlett et al., 1979; Karhu et al., 1981; Keyserling, 1986) have been used. Qualitative descriptions of behavior strategies are useful for conveying the purpose of a posture or motion while quantitative descriptions are useful for assigning statistical significance and rigorously differentiating among strategies. For example, Authier et al. (1996) qualitatively compared the postural strategies (defined by varied foot positions) of experienced versus novice handlers performing self-paced lifts. Delisle et al. (1999) quantitatively compared two of the experienced and novice lifting strategies defined from that study. It was reported that the expert strategies either reduced the path of the center of gravity of the lifter or reduced the asymmetry of the posture at the delivery when compared with the novice strategies. Those changes were attributed to the different stepping patterns between the four strategies. Effective comparisons may benefit from the concordance of both qualitative and quantitative descriptors. Qualitatively defined strategies are best defined with a vocabulary that sufficiently characterizes the set of feasible kinematic configurations. For example, grip posture vocabularies have been used to establish common terminology (Schlesinger, 1919; Cutkosky et al., 1986) for defining differing grip behaviors.

A similar vocabulary for lower extremity behaviors during manual material handling tasks, particularly those associated with non-cyclical stepping, has not been defined. Terms used to describe the stance during load manipulation are not consistently used in the literature. Transverse, split, even, and parallel have been used inconsistently in describing stance. In contrast, the gait literature, which addresses cyclical stepping has adapted a common set of definitions (Whittle 2002). Single support phase, double support phase, heel strike, and toe off are just a few of the well-understood terms in the common vocabulary for linear and non-linear walking (Huxham 2005). Unfortunately, the cyclical stepping vocabulary does not sufficiently describe many of the observed non-cyclical stepping behaviors and a similar comprehensive vocabulary has yet to be adopted. A classification taxonomy is proposed here that focuses on describing the non-cyclical stepping behaviors for manual material handling pickup and delivery tasks.
Attempts at classifying and analyzing stepping behaviors for turning behaviors (Hase, 1999; Meinhart-Shibata et al., 2005) and lifting transfer tasks (Holbein et al., 1997; Delisle et al., 1999) have not resulted in widely used terminology, possibly because of the relatively narrow scope of these efforts. These studies have focused on a single or small set of stepping patterns, and have not presented a formalized structure capable of describing novel stepping patterns.

To address this issue, the current paper:

1. describes the patterns of foot motions for a large number of workers performing MMH tasks involving loads typical of automotive assembly jobs;
2. presents a classification system for patterns of foot motions; and
3. quantifies the distribution of industrial foot motions that fall within the new classification system.

2.3. Methods

Automotive Assembly Job Analysis

The Automotive Assembly Plant and Operators

Automotive assembly plants assemble vehicles by moving the vehicle past operator stations where each operator performs a defined set of tasks upon the vehicle. The speed the vehicle moves through the assembly plant and each individual operator’s tasks are well prescribed. At the time of this study, the observed assembly plant employed 3039 operators working at over 350 operator stations. Many of the operators perform value added operations to the vehicle by fastening, attaching, mounting, affixing, etc. parts to the vehicle. A significant portion of an operator’s time is taken by part and tool retrieval and placement. Some operators are seated or use manual material lift assists for select tasks, but the majority of lifting and delivery is performed as standing operations without any mechanical assistance.

Job Selection and Decomposition

Job operations were selected from among the operators stations in the plant based on the frequency of MMH events separated by two or more strides, the range of object weights handled, the number of total steps over a job cycle, and the vertical range of manipulation locations within the job. Each job was videotaped with the regularly
assigned operator or the assembly line supervisor for that job. A minimum of five cycles were recorded for each job.

For analysis, each job was decomposed into a series of pickup, delivery, turn, and action tasks. A table of nine variables (Table 2.1) was defined for each task (see Figure 2.1 for example). Evaluators watching a video recording of each task documented values for each variable. The nine variables were selected to qualitatively and quantitatively assess the job requirements (and select operator performance) for each task. A similar set of task variables used in comparable industry survey studies were used as a guide for selecting the variables collected here (Drury et al., 1982; Baril-Gingras et al., 1995; Lortie et al., 1996). Only pickup and delivery transfer tasks are reviewed here. Tasks that involved MMH devices (i.e. lift assists) are not included in this study.
Table 2.1. Descriptions of variables used to identify each transfer task.

<table>
<thead>
<tr>
<th>Rated Variable</th>
<th>Range of Values</th>
<th>Variable Description</th>
<th>Maximum Allowable Range for Consensus Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td>a, ps, pl, pt, ds, dl, dt, t</td>
<td>The type of pickup, delivery or turn that is being performed.</td>
<td>† N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a (action) – action/manipulation (i.e. opening a door)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ps (pickup stay) – approach, pickup part, stay/manipulate part</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pl (pickup leave) – at workstation, pickup part, depart</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pt (pickup transfer) – approach, pickup part, depart</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ds (deliver stay) – approach, deliver part, stay/manipulate part</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>dl (deliver leave) – at workstation, deliver/set down part, depart</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>dt (deliver transfer) – approach, deliver part, depart</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>t (turn) – in stationary posture, reorient body to depart in new direction</td>
<td></td>
</tr>
<tr>
<td>Approach Angle</td>
<td>-180 &lt; &gt; 180 degrees, nan</td>
<td>The approach angle, referenced from the axes defined by the part (Figure 2.2). ‘nan’ is used for tasks that do not have an approach angle.</td>
<td>45 degrees</td>
</tr>
<tr>
<td>Departure Angle</td>
<td>-180 &lt; &gt; 180 degrees, nan</td>
<td>The departure angle, referenced in a similar fashion as the approach angle (Figure 2.2). Angles for Turns are referenced as the change in angle from an initial posture to the final selected direction.</td>
<td>45 degrees</td>
</tr>
<tr>
<td>Pickup/Delivery Height</td>
<td>Meters</td>
<td>Height from the floor of where the load is picked up or delivered.</td>
<td>0.2 meters</td>
</tr>
<tr>
<td>Load Mass</td>
<td>Kilograms</td>
<td>Weight of the load being manipulated. *Load weight is obtained from the Job Information Sheet.</td>
<td>N/A</td>
</tr>
<tr>
<td>*Manipulator Hand</td>
<td>Left, Right, Both</td>
<td>The Hand(s) used to perform the pickup/delivery task.</td>
<td>N/A</td>
</tr>
<tr>
<td>*Contra-lateral Hand Action</td>
<td>Support, Carry, other</td>
<td>Description of the action effort of the contra-lateral hand for one-handed tasks.</td>
<td>N/A</td>
</tr>
<tr>
<td>*TRACS Coding</td>
<td>See section 2.2</td>
<td>L-Vector identification</td>
<td>N/A</td>
</tr>
<tr>
<td>*Turn Direction</td>
<td>Left, Right</td>
<td>Direction the pelvis rotates during the lifting MMH event.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Variables defined by operator performance
† N/A denotes that a range for determining consensus was not applicable for those rated variables
Figure 2.1. Representative video clip of a pickup transfer task and the associated rated values. Pictures are presented chronologically (1-6).

Rating Methodology

Three raters coded each task. The raters were instructed that pickup and delivery transfer tasks were required to contain at least one walking stride along the approach and departure vectors prior to and following the MMH event. Transitions that included shuffle or intermediate steps during the task to maintain pace with the moving line (when applicable) were not defined as transfers, but as stays or leaves. A comprehensive task list in which at least one rater identified the task as a transfer was compiled. Individual raters were then asked to reevaluate each task included on the comprehensive list for accuracy in variable identification and transcription. A consensus rating for each task in the revised comprehensive list was constructed using the following two-step methodology:

1. Automatically assign a consensus value if concordance (nominal variables) or a minimum range (continuous variables) of the independent rater values is achieved. Table 2.1 lists the maximum range allowed among the raters for each continuous variable to be automatically identified.

2. Group discussion and consensus between the raters for each remaining task variable.

The approach and departure angles for each task are defined using the manipulation axes \((X_M, Y_M)\), as shown in Figure 2.2. The manipulation axes are defined by the nominal parallel stance that would be adopted if both hands were used to manipulate the part at the manipulation location for an extended period of time (Figure 2.2).
2.2), i.e. with the worker ‘facing’ the job. The manipulation axes are defined primarily by part and workspace orientation layout. The ‘forward’ direction could usually be readily defined by the orientation of a parts bin, work table, or other element of the work environment. Manipulation axes for hanging tools involved in pickup and deliveries were defined such that the approach angle was assigned to 180 degrees.

Figure 2.2. Pictorial representation of the approach and departure angle convention. Approach and departure angles are defined along the path the approach and departure follows.

Data Presented

Forty-two jobs from the production line of an automotive assembly plant were each videotaped for 5 job cycles and rated independently by three experienced raters. Each job included approximately 7 tasks. A total of 1312 tasks were reviewed. Only tasks that were categorized by all raters as a transfer (pickup or delivery) are presented here. Push/pull exertions, tasks involving more than one operator, or ones in which a mechanical lift assist was used, are excluded from the analysis. A total of 529 transfer tasks performed by 30 different operators in 32 different jobs are presented.

Statistical Analysis

Two classification results are presented. First, the distribution of job requirements and the reliability of independent raters classifying those MMH tasks are presented. Second, the distribution of observed transition behaviors and the reliability of
the independent raters for identifying those behaviors using a new transition classification system are presented. The entire statistical analysis was performed using the ‘R’ statistical software package (http://www.r-project.org/).

Transition Stepping and Classification System (TRACS)

An important observation of this research is that a large majority of foot behaviors in manual materials handling (MMH) tasks are consistent with a small number of basic patterns. The Transition Classification System (TRACS) was developed to address the need for a well-defined and complete system for describing these behaviors. Each TRACS representation of a stepping behavior includes separate descriptive and quantitative representations. The Lexical Transition Classification Sub-System (L-TRACS) defines the descriptive representation while the Quantitative Transition Classification Sub-System (Q-TRACS) defines a quantitative transition behavior representation. L-TRACS is intended to be used for comparing and grouping behaviors with similar step progressions while Q-TRACS uniquely defines the position and associated foot events for each step within a behavior (Wagner et al., 2006). The formulation of L-TRACS is presented in this paper.

Lexical Transition Classification Sub-System (L-TRACS)

The Lexical Transition Classification Sub-System (L-TRACS) is a method for qualitatively describing a transition-stepping behavior. L-TRACS was developed to concisely identify the following attributes of the lower extremities shown to be of interest for ergonomic and postural assessment. Select effects of each attribute as related to the potential interest toward ergonomic and postural assessment are described (discussed in further detail later).

1. Terminal Stance (relative configuration); shown to affect postural control and stability when lifting loads (Kollmitzer et al., 2002).

2. Terminal Stance Ground Contact; observed discrepancy between MMH observations in which single limb support is a prevalent strategy (Ljungberg et al., 1989; Authier et al., 1996) and those postures used during prospective ergonomic analyses in which simulated terminal postures with single limb support are rare (Stephens et al., 2006).
3. Number of Steps; shown to relate to lifting strategies associated with protecting the back during asymmetrical lifting (Gagnon et al., 1993); can be interpreted as a potential measure of stability (Lipsitz et al., 1991).

4. Type of Step; proposed common vocabulary to differentiate between the acyclic steps used during load transfer tasks. For example, not all steps are equivalent to those observed during cyclic gait and should be distinguished as such.

An L-TRACS description includes the steps that define the terminal stance at the MMH transition event (pickup or delivery of an object) and the preceding and succeeding non-cyclical steps. The terminal stance is defined as the relative foot placements with respect to the load position at the instant of pickup or delivery (i.e. when the weight of the object is initially borne by the lifter (pickup) or by the target location (delivery)). Ipsilateral and contralateral limbs are defined with respect to the turn direction. For example, a right turn (clockwise from above) defines the right lower extremity as the ipsilateral limb. Split (feet spread apart as seen in the double support phase of a gait cycle) and even (feet side-by-side) terminal stances are further modified in the L-TRACS lexicology with ground contact information of the heel and toe at the lifting MMH event. This modified terminal stance is defined here as the terminal posture state.

The L-Vector and Step Definition

Each L-TRACS description is represented by a vector L where L is given by:

\[ L = [\Sigma_p, p, \Sigma_s], \]

where \( \Sigma_p \) and \( \Sigma_s \) describe the steps preceding and succeeding, respectively, the terminal posture state described by \( p \). \( \Sigma_i \) is a sequence of steps given by:

\[ \Sigma_i = [\sigma_1, \ldots, \sigma_n], \]

where \( \sigma_j \) represents a step. The subscript \{I, C\} indicates whether the step is performed by the ipsilateral or contralateral lower extremity (Table 2.2). Four step class elements \{S, P, O, M\} are used to represent progression, pivot, orient, and move steps, respectively, which are defined in the following section. The order of steps in \( \Sigma_i \) is sequential in time such that the time of the first foot contact event for step \( \sigma_i \) is strictly less than the time of the first contact event of step \( \sigma_{i+1} \).
Table 2.2. Characters concatenated to represent a single step. A step is comprised of one step class element and one subscript foot element.

<table>
<thead>
<tr>
<th>Element Description</th>
<th>Step Characters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Class</td>
<td>S : Progression</td>
</tr>
<tr>
<td>Element</td>
<td>P : Pivot</td>
</tr>
<tr>
<td></td>
<td>O : Orient</td>
</tr>
<tr>
<td></td>
<td>M : Move</td>
</tr>
<tr>
<td>Subscript Foot</td>
<td>I : Ipsilateral Foot</td>
</tr>
<tr>
<td>Element</td>
<td>C : Contralateral Foot</td>
</tr>
</tbody>
</table>

The following definition of a foot event is used here to describe the transition between the ground contact states of each step. A foot event is defined as the change in contact state with the ground for the toe or heel segment of the foot. The four types of foot events are:

1. Heel Contact (HC)
2. Toe Contact (TC)
3. Heel Lift (HL)
4. Toe Lift (TL)

Contact foot events are defined as the transition from a non-contact to contact state with the ground. Lift foot events are defined as the transition from a contact to non-contact state with the ground.

A step is defined as a sequence of at most four unique foot events. A step is further defined by the following five criteria:

1. A step must contain at least one HC or TC foot event.
2. A step must contain no more than four foot events.
3. A step must contain no duplicate foot event.
4. The preceding step of the same foot must contain a TL or HL for each TC or HC contained within the current step, respectively.
5. If a Heel or Toe contact foot event occurs, the next Heel or Toe foot event must be a lift, respectively. The contact and lift do not need to occur in the same step.

This representation of a step can also be used to quantitatively parameterize bipedal ambulation (Wagner et al., 2006). Due to the limitations of the data collection methods in this study, the steps of the observed transition behaviors could not be identified in a similar fashion.
Definition of an L-TRACS Step

The core of the L-TRACS system is the definition of a step. Transition stepping behaviors are represented using four unique step types: *progression, pivot, orient,* and *move*, which are represented by the symbols, \( S, P, O, \) and \( M \), respectively (see Table 2.2). Progression and move steps are defined as having a primarily translational effect on the pelvis while pivot and orient steps are defined as having a primarily rotational effect. The steps observed during normal cyclic locomotion are classified as progression steps. Pivot, orient, and move steps are defined as preparatory steps and are observed during object manipulation and turning. An example of each step type is depicted in Figure 2.3 and the criteria used for identifying each step type are described below.

Progression steps satisfy the following criteria:

1. Translation of the pelvis occurs along the direction of progression.
2. A foot event sequence of: [heel contact, toe contact, heel lift, and toe lift].
3. One of the following step length and angle criteria combination (a, b, or c, below). The step length criteria (i) are defined as a minimum allowable step length (Euclidean distance projected onto the direction of progression). The angle criteria (ii) are defined as a maximum allowable included angle between the orientation of the foot and the direction of progression. The values associated with the minimum step length and maximum angle criteria were selected based on observation from the transfers in the automotive assembly plant. Due to the limitations of
estimating distances and angles from video recordings, the values listed below should be interpreted as guidelines to assist the raters as opposed to quantitative criteria that distinguish one particular step from another. For example, the estimates of step length are derived from comparisons to the length of the operator’s foot in an attempt to assist the video raters in consistently identifying the type of step.

a. Moderate minimum step length and moderate allowable included angle
   i. $3 \times (\text{foot length})$
   ii. 30 degrees

b. Small minimum step length and small allowable included angle
   i. $1 \times (\text{foot length})$
   ii. 10 degrees

c. Large minimum step length only
   i. $4 \times \text{foot length}$
   ii. no limit

The three criteria conditions are used to accommodate the variability associated with this step across the observed transfer tasks. Due to the limitations of the available job recordings in addition to the required task of estimating the changes in angles and distances of sequential steps from video recordings, it was difficult to identify one single criteria that could satisfactorily be applied to the majority of transfer task conditions, particularly to distinguish between a progression step along a curved path and an orient step (defined later). The criteria attempt to address that difficulty with three alternative sets of step length and foot orientation criteria that can be more simply stated as a) a moderate step length with the foot fairly well aligned with the direction of progression, b) a small step length with the foot closely aligned with the direction of progression or, c) a large step length.

*Pivot* steps occur when the worker reorients the foot without lifting it fully from the ground. Pivot steps satisfy the following criteria:

1. The step is not a progression step.
2. The previous step of the same foot ends with the toe in contact and the heel not in contact with the ground (i.e. the toe has remained in contact with the ground).

3. A heel contact event occurs before a toe lift event during the current step.

4. At least a minimum observable change in foot orientation as compared to the previous step of the same foot. A guideline of 15 degrees was defined from observations of the automotive assembly plant transfer tasks.

**Orient** steps are defined by satisfying the following criteria:

1. The step is not a progression or pivot step.

2. The previous step of the same foot ends with the heel and toe not in contact with the ground (i.e. the foot is not touching the ground).

3. A minimum observable change in foot orientation as compared to the previous step of the same foot. The same guideline used for pivot step identification of 15 degrees was also used here.

Steps that do not satisfy the *progression*, *pivot*, or *orient* criteria are classified as *move* steps. For example, an *orient* or *pivot* step that does not change in orientation would be classified as a *move* step.

One exception with the criteria above for defining the sequence of steps prior to the terminal posture state ($\Sigma_p$) occurs when defining the first *progression* step of a behavior. The exception occurs for the 2nd criteria, which states *progression* steps must follow the foot event sequence of heel contact, toe contact, heel lift, toe lift. However, in certain cases, the heel lift and toe lift may occur in the opposite order or potentially only one of the lift events may occur before the next step. This exception was introduced to present a more concise L-vector for the majority of the behaviors in which the two steps prior to the terminal stance and the two steps that comprise the terminal stance are equivalent. Similarly, because of the difficulty in distinguishing between progression and move steps from the video recordings for the step immediately prior to the terminal stance, the raters were instructed to always use a preparatory step classifier to describe that step.

For example, the departure step sequence $\Sigma_d = [P_C, S_I]$ is read from left to right as ‘a pivot step with the contralateral foot followed by a progression step with the ipsilateral
foot'. This $\Sigma_d$ sequence is graphically depicted in Figure 2.4.B in which $P_c$ and $S_i$ are labeled as steps 3 and 4, respectively.

When the foot remains in contact with the ground, but translates or orients (i.e. the foot appears to ‘slide’ across the ground), it is assumed that the weight being supported by that foot is negligible. In these cases, the steps are classified as above except the contact/no contact ground criteria are replaced with the supporting weight/not supporting weight criteria, respectively.
Figure 2.4. Example of each step class element. Steps are numbered in the order in which they first contact the floor. The terminal stance is represented by steps 1 and 2. The L-TRACS Vector is given in the brackets {} for each right turn scenario. Examples of a A) Progression, B) Pivot, C) Move, and D) Orient step are shown.

**Terminal Posture State**

The terminal posture state $p$ represents the terminal stance and ground contact state of each foot at the transfer MMH event. The terminal posture state $p$ is given by:

$$p = [\tau, \gamma],$$

where
where \( \tau \) is a terminal stance element \{I, C, E\} (Figure 2.4) and \( \gamma_c \) and \( \gamma_i \) are terminal stance contact element subscripts giving the ground contact status for the contralateral and ipsilateral foot respectively (Table 2.3). The characters \{T, H, B, N\} are used to indicate that the toe, heel, both toe and heel, or neither are in contact with the ground. The foot whose projection onto the direction of progression vector is closer to the load at the lifting MMH event defines the terminal stance element \( \tau \). In the special case where the anterior/posterior distance between the ipsilateral and contralateral heel positions projected onto the direction of progression vector of the approach is less than a single foot length, an even terminal stance \{E\} is defined. The terminal stance contact element \( \gamma_k \) defines the segments of the foot (heel and toe) that are in contact with the ground at the lifting MMH event. For example, the terminal posture state ‘C_{BT}’ represents a split stance with the contralateral foot, with respect to the direction of turn, as the lead foot, both the heel and toe contacting the ground for the contralateral foot \{B\}, and the toe on the ground with the heel lifted up for the ipsilateral foot \{T\}. An example of four transition behaviors and the associated L-TRACS representation are depicted in Figure 2.5 and Figure 2.6.

Table 2.3. Characters concatenated to represent the terminal posture state. A terminal posture state is comprised of one terminal stance element and two subscript terminal stance contact elements.

<table>
<thead>
<tr>
<th>Element Description</th>
<th>Terminal State Characters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal Stance Element</td>
<td>I : Split Stance, Ipsilateral Lead Foot</td>
</tr>
<tr>
<td></td>
<td>C : Split Stance, Contralateral Lead Foot</td>
</tr>
<tr>
<td></td>
<td>E : Even Stance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscript Terminal Stance Contact Element</th>
<th>Terminal State Characters</th>
</tr>
</thead>
<tbody>
<tr>
<td>T : Toe Ground Contact Only</td>
<td>T : Toe Ground Contact Only</td>
</tr>
<tr>
<td>H : Heel Ground Contact Only</td>
<td>H : Heel Ground Contact Only</td>
</tr>
<tr>
<td>B : Heel and Toe Ground Contact</td>
<td>B : Heel and Toe Ground Contact</td>
</tr>
<tr>
<td>N : No Ground Contact</td>
<td>N : No Ground Contact</td>
</tr>
</tbody>
</table>
Figure 2.5. Two example split stance transition behaviors observed in the assembly plant with select rated measures. The L-TRACS description for each behavior is A) $S_C M_I I_{NB} O_C S_I$ B) and $S_I M_C C_{BN} S_I$.
2.4. Results

Automotive Assembly Job and Task Descriptions

In this section, a description of the operators and the types of transfer tasks observed is presented based on the consensus description for each task. Start and end body positions before and after each MMH event were classified with approach and departure angles respectively. The task and object descriptions were classified by the
manipulation height, object weight, hand used during the manipulation, and object configuration (part size/description identified from Job Information Sheet provided by the assembly plant staff). During one-handed manipulations, the action of the contralateral hand is presented to describe the behavior and/or constraints imposed by the opposing hand during the manipulation task. The inter-rater reliability is presented for each task element.

Operator Statistics

Twenty-five male and five female experienced operators ranging in age from 27 to 55 were observed performing 32 automotive assembly jobs. The level of experience varied across operators. Each operator’s primary job (i.e. the operation where their majority of time is spent) was the operation or direct supervision of the operation under observation. Summary statistics (mean ± standard deviation) for male and female operator characteristics are, respectively: stature (1.793 ± 0.083 m, 1.596 ± 0.086 m), weight (92.8 ± 15.2 kg, 66.8 ± 8.5 kg), and body mass index (28.8 ± 3.9 kg/m², 26.2 ± 2.2 kg/m²).

Object Configuration, Height, Weight, and Transfer Hand

The type of manipulation and the hand(s) used to manipulate the load during the lifting MMH event were used to classify the transfers. The number of times each of the six classes of transfers (pickup/delivery for left/right/both hands) were observed are presented in Table 2.4. Right-handed pickup manipulations accounted for the largest class (32.9%) of the total number of observed transfers while left-handed deliveries accounted for the smallest class (3.2%).

Table 2.4. Frequency of the observed transfers classified by manipulation type and hand.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Left Hand</th>
<th>Pickup</th>
<th>Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right Hand</td>
<td>Both Hands</td>
<td>Left Hand</td>
</tr>
<tr>
<td>Frequency Count</td>
<td>60</td>
<td>174</td>
<td>115</td>
</tr>
<tr>
<td>% total within pickup or delivery</td>
<td>17.2</td>
<td>49.9</td>
<td>33.0</td>
</tr>
<tr>
<td>% total overall</td>
<td>11.3</td>
<td>32.9</td>
<td>21.7</td>
</tr>
</tbody>
</table>

The majority of parts and tools transferred were of negligible weight (i.e. screws, fasteners, clips, etc.) and are represented here as having a weight of zero (Figure 2.7). The majority of one-handed transfers consisted of negligible weighted parts while the
The majority of two-handed transfers consisted of 5-10 kg parts or tools. As noted above, jobs involving transfers with multiple operators and/or lift assist devices were excluded from this study.

![Histograms showing object manipulation weight for one-handed and two-handed pickup and delivery transfer tasks.](image)

Figure 2.7. Object manipulation weight for one-handed and two-handed pickup and delivery transfer tasks.

Manipulation heights ranged from 0.4 m to 1.9 m. Of the pickup transfers, 77.9% occurred between 1 m and 1.4 m while only 61.9% of the delivery transfers occurred within the same range (Figure 2.8). One-handed pickup manipulations spanned the entire observed manipulation height range. Two-handed pickup and one and two-handed delivery manipulations were observed to each occur within a 1-m height range.
Approach, Departure, and Included Transfer Angles

Approach and departure angles for all transfer tasks are referenced using the two-handed transfer coordinate reference frame (Figure 2.2) defined by the part and work-cell layout geometry. Angular probability density distributions for the approach, departure, and included transfer angles are presented in Figure 2.9 for the pickup and delivery task conditions. Eighteen-degree angular bin sizes are used for each histogram. References to each angular bin are made with respect to the angular value bisecting that bin.
Figure 2.9. Approach, departure, and included angle density distributions classified by manipulation type (pickup and delivery) and turn direction (for included angles only). Included angle density distributions for the left and right turn directions are presented on the same plot.

Approach occurred most frequently along the 180° direction for the pickup (27.5%) and delivery (34.4%) transfer tasks (Figure 2.9). Positive and negative 90° approach directions accounted for more than 10% of all transfers for both the pickup and delivery transfer conditions. A small number of approach directions for both the pickup and delivery conditions (1.1% for each condition) occurred between the +72° and -72° (0° inclusive) angular bins. The remaining approaches for both task conditions occurred between the positive and negative 108° and 162° bin areas respectively.

Departure occurred most frequently along the +90° and -90° directions for the pickup (20.3% and 25.2% respectively) and delivery (17.8% and 22.8%, respectively) task conditions (Figure 2.9). For the pickup tasks, 5.5% of departure directions were between positive and negative 72°. The remaining departure angles for the pickup transfers (49.0%) occurred between positive and negative 108°. 12.2% of all departure directions for the delivery transfer tasks occurred within the 180° angular bin. The remaining departure directions were distributed among the remaining bins with an average of 2.8% of departures per bin.
The angle through which the pelvis must rotate between the approach and departure vectors is presented here as the included angle (Figure 2.9). For example, a transfer with a left turn direction (counterclockwise) and an approach and departure angle of 135° and -90° respectively results in an included angle of 45°. Left and right turns are independently plotted for the included angles on Figure 2.9 as counterclockwise and clockwise angles respectively. Counterclockwise angles are defined here as negative. 54.2% and 48.3% of the transition turns were toward the left direction for the pickup and delivery transfers respectively. 9.0% and 8.1% of the included angles for the left and right turn directions for the pickup transfer tasks were greater than 180° respectively. Included angles in the 180° ± 9° angular bin for left and right turns occurred most frequently (21.2% and 30.6% respectively) for the pickup transfers. 9.2% and 6.5% of the included angles for the left and right turn directions for the delivery transfer tasks were greater than 180° respectively.

Contra-lateral Hand

Of the one-handed transfers, 19.7% occurred with a contra-lateral hand effort. For example, if the left hand is used to perform a lift, the right hand is defined as the contralateral hand and the efforts described here are made with respect to that hand. The majority of the contra-lateral hand efforts occurred during pickup type transfers (91.3%). Contralateral handed carry efforts (i.e. the hand opposite that performing the lift is holding another part or object) were most frequent during pickup transfers and accounted for 67.4% of the pickup transfers with a contra-lateral effort. Contralateral handed support efforts (i.e. the hand opposite that performing the lift is used to brace the body against an external structure while the lift is performed) were most frequent during delivery transfers and accounted for 55.6% of the delivery transfers that included a contra-lateral effort. Right and left handed contra-lateral efforts occurred in 36.0% and 22.3% of all right and left handed transfers respectively.

Inter-rater Reliability

Inter-rater reliability was assessed between the independent ratings performed by each rater and the subsequent consensus rating for each rated measure. The percent of raw agreement, the intraclass correlation coefficient (ICC) (Shrout et al., 1979), and the 95% confidence interval on the ICC are presented for the continuous variables
(manipulation height, approach angle, departure angle, and included angle) rated to
describe each task (Table 2.5). Object weight was not evaluated because those values
were provided by the assembly plant and not evaluated by the individual raters. The ICC
was selected based on guidelines proposed by Shrout et al. (1979) to be a two-way single
measure for absolute agreement reliability rating. Tolerances for the percent of raw
agreement were set at 0.3 m for the height ratings and 20 degrees for the angle ratings
where the maximum minus the minimum rating was required to be less than the tolerance
value for the task to be accepted as ‘in agreement’. Tasks in which a rater could not
identify the measure in question were excluded from the ICC calculation. Approximately
9% of the rated trials included at least one variable with a missing rating.

Table 2.5. Inter-rater reliability of measurements for continuous variables.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Percent of raw agreement (%)</th>
<th>ICC</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulation Height</td>
<td>73.4</td>
<td>0.728</td>
<td>0.693 &lt; ICC &lt; 0.760</td>
</tr>
<tr>
<td>Approach Angle</td>
<td>72.5</td>
<td>0.782</td>
<td>0.753 &lt; ICC &lt; 0.809</td>
</tr>
<tr>
<td>Departure Angle</td>
<td>65.0</td>
<td>0.709</td>
<td>0.672 &lt; ICC &lt; 0.743</td>
</tr>
<tr>
<td>Included Angle</td>
<td>60.1</td>
<td>0.763</td>
<td>0.729 &lt; ICC &lt; 0.794</td>
</tr>
</tbody>
</table>

Inter-rater reliability measures of the percent of raw agreement, kappa statistic
(Fleiss 1971), and the category-wise kappas are presented for the nominal variables (task
type, manipulator hand, step direction, and step behavior identification) rated to describe
each task (Table 2.6). Inter-rater reliability for the identification of the step behavior is
presented in section 3.2.3 (Table 2.8). The kappa statistic is interpreted as a measure of
rater agreement beyond chance agreement. The category-wise kappas can be interpreted
as a ‘statistic to measure the extent of agreement in assigning a subject [defined here as a
task] to a particular [nominal] category’, Shoukri (2004). Inter-rater reliability among the
three raters was ‘excellent’ as defined by Fleiss (1981) and ‘substantial’ to ‘almost
perfect agreement’ by Landis et al. (1977) for the nominal task description elements of
task type, manipulator hand, and turn direction. The interpretation of kappa by Landis
and Koch (1977) is used here because of the greater fidelity included in that scale. All
three raters were required to identify the same nominal value for a task to be accepted as
‘in agreement’.
Table 2.6. Inter-rater reliability of measurements for nominal variables.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Percent of raw agreement (%)</th>
<th>Kappa</th>
<th>Category-wise Kappas*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Type</td>
<td>91.7</td>
<td>0.884</td>
<td>a: 0.499</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>dl: -0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ds: -0.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>dt: 0.931</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pl: -0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ps: -0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pt: 0.942</td>
</tr>
<tr>
<td>Manipulator Hand</td>
<td>79.6</td>
<td>0.775</td>
<td>B: 0.759</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>L: 0.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R: 0.854</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Null: 0.322</td>
</tr>
<tr>
<td>Step/Turn Direction</td>
<td>92.4</td>
<td>0.897</td>
<td>L: 0.914</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R: 0.909</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Null: 0.227</td>
</tr>
</tbody>
</table>

*see Table 2.1 for category descriptions

TRACS Behaviors

The types and frequency of the observed patterns of foot movements, classified using TRACS, are presented. A grouping technique for the TRACS behaviors was used that clusters the behaviors based on the number of steps, progression of steps, and the terminal stance. Correct identification of a TRACS behavior by the raters using L-TRACS is evaluated. Inter-rater reliability measures for classifying an individual behavior and the behavior group are presented.

Results for L-TRACS Behaviors

Thirty-eight unique L-TRACS behaviors were identified in the video analysis. The behavior ‘$S IMC BN S$’ was observed most frequently and accounted for 30.5% of the pickup and 29.3% of delivery transfer behaviors (Figure 2.10). This L-TRACS code is interpreted as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_2$</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).</td>
</tr>
<tr>
<td>$M_C$</td>
<td>The step immediately prior to the terminal posture is a move step (S) with the contralateral foot (C).</td>
</tr>
<tr>
<td>$C_{BN}$</td>
<td>In the terminal posture, the contralateral foot (C) is forward, and both the heel and toe are in contact with the floor (B). The ipsilateral foot is not in contact with the ground (N).</td>
</tr>
<tr>
<td>$S_l$</td>
<td>The first step following the load transition (pickup or delivery) is with the foot on the side of the departure direction.</td>
</tr>
</tbody>
</table>
There exist a large number of methods for characterizing L-TRACS behaviors across similar elements. One such grouping scheme that combines L-TRACS behaviors with similar 1) numbers of steps, 2) lead foot at terminal stance, 3) and sequence of steps (i.e. contralateral vs. ipsilateral) is considered. Another way to describe the scheme is by the L-TRACS elements that are combined into the similar groups. Those elements here are the ground contact states at terminal stance and the type of preparatory step (i.e. progression, move, orient) for each of those steps in the behavior. There are two primary aspects that facilitated the selection of such a grouping scheme. The first is motivated by limitations of the methods in being able to identify the elements that were grouped from the video data. As previously mentioned, the fidelity of the video prohibited perfect identification of heel and toe ground contact states at the terminal stance, particularly
when the heel was being lifted off the ground. A similar limitation for distinguishing the type of step (for which the criteria were not strictly defined) was also encountered. By grouping across those elements, the error associated with misidentifying those elements was limited. The second motivating aspect to this grouping scheme is for future applications in modeling these data for prospective type motion prediction. The types of steps are distinguished by relative changes in position and orientation, traditionally modeled as continuous variables. The one exception is the pivot step, which does not have an associated change in foot position, only orientation. However, even this is not necessarily a nominally different characteristic, but only a constraint on an already existing continuous variable. The ground contact states during terminal stance are not continuous, but nominal elements. However, as further discussed in Chapter 5, these elements may be more suited to be evaluated through kinematic constraints of the foot positions and task requirements than defined outright, potentially leading to kinematically infeasible (or out of balance) postures.

For example, individual behaviors with the only difference being in the ground contact during terminal stance (i.e. $S_I M_c C_{BT} S_I$, $S_I M_c C_{BT} S_I$, $S_I M_c C_{BB} S_I$) would be included in the same behavior group. Another example includes grouping individual behaviors in which the only difference is the type of preparatory step used immediately following the terminal posture (i.e. $S_c M_I I_{BT} P_c S_I$, $S_c M_I I_{BT} O_c S_I$, $S_c M_I I_{BT} M_c S_I$, would be grouped together). For clarity, behavior groups are identified using the related code that includes both heel and toe in contact with the floor {B} for both feet during the terminal stance (i.e. the behavior group for the $S_I O_c C_{BB} S_I$ individual behavior is $S_I O_c C_{BB} S_I$). Additionally, preparatory steps are all identified in the behavior group using the orientation {O} step (i.e. the behavior group for the $S_c M_I I_{BT} P_c S_I$ individual behavior is $S_c O_I I_{BB} O_c S_I$). The final five chosen behavior groups accounted for over 90% of all observed pickup and delivery transfer groups (Figure 2.10.B). Behaviors accounting for less than 1% of the total observed transfers are further grouped together and presented in the ‘additional’ category. A more detailed description of the five most commonly observed behavior groups is presented in Table 2.7. The individual behaviors observed in the analyzed tasks that comprise each behavior group are also presented.
Table 2.7. Step descriptions for the five most common behavior groups.

<table>
<thead>
<tr>
<th>Step Behavior Group</th>
<th>Individual Behaviors</th>
<th>Step or Terminal Posture</th>
<th>Step or Terminal Posture Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{O_c}C_{\text{in}}S_1 )</td>
<td>( S_{M_{C_{\text{in}}}S_1} ), ( S_{M_{C_{\text{in}}}S_1} ), ( S_{M_{C_{\text{in}}}S_1} ), ( S_{O_{C_{\text{in}}}S_1} ), ( S_{O_{C_{\text{in}}}S_1} ), ( S_{O_{C_{\text{in}}}S_1} )</td>
<td>( S_1 )</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_C )</td>
<td>The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( C_{\text{in}} )</td>
<td>In the terminal posture, the contralateral foot (C) is forward.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( S_1 )</td>
<td>The first step following the load transition is with the foot on the side of the departure direction.</td>
</tr>
<tr>
<td>( S_{O_c}E_{\text{in}}S_1 )</td>
<td>( S_{M_{E_{\text{in}}}S_1} ), ( S_{M_{E_{\text{in}}}S_1} ), ( S_{O_{E_{\text{in}}}S_1} ), ( S_{O_{E_{\text{in}}}S_1} )</td>
<td>( S_1 )</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_C )</td>
<td>The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( E_{\text{in}} )</td>
<td>In the terminal posture, the both feet are even (E) with one another.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( S_1 )</td>
<td>The first step following the load transition is with the foot on the side of the departure direction.</td>
</tr>
<tr>
<td>( S_{C_{\text{in}}}I_{\text{in}}O_{\text{in}}S_1 )</td>
<td>( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_1} ), ( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_1} ), ( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_1} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_1} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_1} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_1} )</td>
<td>( S_C )</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the contralateral foot (C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_I )</td>
<td>The step immediately prior to the terminal posture is a preparatory step with the ipsilateral foot (I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( I_{\text{in}} )</td>
<td>In the terminal posture, the ipsilateral foot (I) is forward.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( S_1 )</td>
<td>The second step following the load transition is a progression step (S) with the ipsilateral foot (I) along the new direction of progression.</td>
</tr>
<tr>
<td>( S_{O_c}E_{\text{in}}O_{\text{in}}S_1 )</td>
<td>( S_{M_{E_{\text{in}}}O_{\text{in}}S_1} ), ( S_{M_{E_{\text{in}}}O_{\text{in}}S_1} ), ( S_{M_{E_{\text{in}}}M_{I_{\text{in}}}S_1} ), ( S_{M_{E_{\text{in}}}M_{I_{\text{in}}}S_1} ), ( S_{M_{E_{\text{in}}}M_{I_{\text{in}}}S_1} )</td>
<td>( S_1 )</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_C )</td>
<td>The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( E_{\text{in}} )</td>
<td>In the terminal posture, the both feet are even (E) with one another.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_C )</td>
<td>The first step following the load transition is with the foot on the opposite side of the departure direction.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( S_1 )</td>
<td>The second step following the load transition is a progression step (S) with the ipsilateral foot (I) along the new direction of progression.</td>
</tr>
<tr>
<td>( S_{C_{\text{in}}}I_{\text{in}}S_C )</td>
<td>( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_C} ), ( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_C} ), ( S_{M_{I_{\text{in}}}M_{I_{\text{in}}}S_C} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_C} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_C} ), ( S_{M_{I_{\text{in}}}O_{\text{in}}S_C} )</td>
<td>( S_C )</td>
<td>The second-to-last step before the terminal posture is a progression step (S) with the contralateral foot (C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( O_I )</td>
<td>The step immediately prior to the terminal posture is a preparatory step with the ipsilateral foot (I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( I_{\text{in}} )</td>
<td>In the terminal posture, the ipsilateral foot (I) is forward.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( S_C )</td>
<td>The first step following the load transition is with the foot on the opposite side of the departure direction.</td>
</tr>
</tbody>
</table>

L-TRACS Elements

The number of non-cyclical steps used to perform a transition behavior ranged from 3 to 7. The majority of observed behaviors used 3 or 4 steps, accounting for 72.6% and 24.6% of all observed transitions respectively. The predominant terminal stance observed was split (71%) with 30% of those split behaviors with the ipsilateral limb as the lead foot and the remaining 70% with the contralateral limb as the lead foot (Figure...
Single limb ground contact terminal stance occurred during 68.4% of all transitions. Full (both heel and toe for each foot in contact with the ground) and partial limb stance consisted of the remaining observed stances at 19.7% and 11.9% respectively.

Figure 2.11. Distributions of the ground contact conditions within the three terminal stances and as % of all observations.

**L-TRACS Identification and Rater Reliability**

Inter-rater reliability measurements are presented for complete L-TRACS behaviors and the elements used to define those behaviors (Table 2.8). Agreement is defined for two individual L-TRACS behaviors if and only if the two behaviors have the same L-Vector. Agreement is achieved for two grouped L-TRACS behaviors if the two behaviors belong to the same behavior group. The chance-corrected agreement statistic (kappa) for individual behavior identification is 0.326 and for grouped behavior identification is 0.483. Rater agreement for the number of steps and terminal stance element was 68.2% and 56.3% respectively for all transfer trials. The category-wise kappas for the even, ipsilateral lead split, and contralateral lead split stance were 0.573, 0.662, and 0.548 respectively. The individual L-TRACS kappa agreement was interpreted as ‘fair’ (Fleiss, 1981). The grouped L-TRACS, number of steps, and terminal stance kappa agreement were interpreted as ‘moderate’ (Fleiss, 1981).
Table 2.8. Inter-rater reliability of measurements for L-TRACS behaviors, groups, and element variables.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Percent of raw agreement</th>
<th>Kappa (Fleiss 1971)</th>
<th>Category-wise Kappas</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-TRACS Behavior (individual)</td>
<td>24.8</td>
<td>0.326</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-TRACS Behavior (grouped)</td>
<td>46.9</td>
<td>0.483</td>
<td>*</td>
</tr>
<tr>
<td>Number of Steps</td>
<td>68.2</td>
<td>0.557</td>
<td>3 steps: 0.593</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 steps: 0.694</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 steps: 0.197</td>
</tr>
<tr>
<td>Terminal Stance</td>
<td>56.3</td>
<td>0.536</td>
<td>Contralateral: 0.548</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Even: 0.573</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ipsilateral: 0.662</td>
</tr>
</tbody>
</table>

*denotes more than 10 nominal categories

2.5. Discussion

This study proposed a method for classifying transition stepping behaviors during manual material handling tasks and applied that system to identifying those behaviors used during selected jobs by operators in an automotive assembly plant. The tasks spanned a wide variety of manipulation heights, object type, object weights, and floor layouts. Similar demands on human operators have been observed in other MMH studies across industries (Drury et al., 1982; Baril-Gingras et al., 1995). The variety of job requirements combined with the infinite number of kinematically feasible stepping behaviors creates a large number of possible stepping patterns that could be chosen to satisfy the variety of task requirements. However, a relative small number of stepping patterns (five L-TRACS behavior groups) accounted for over 90 percent of the observed foot movement patterns. A single L-TRACS behavior group accounted for over 30% of all observed behaviors.

The observed task requirements and terminal posture states of split and single limb stance differ substantially from the predominant postures and tactics examined in lifting research over the past 30 years (Bendix et al., 1983; Holbein et al., 1997; Burgess-Limerick et al., 1998). Sagittal plane lifts with no horizontal component are frequently studied (Ayoub et al., 1995; Ayoub, 1998); yet represent a small portion of the lifts performed in industry (Baril-Gingras, 1995). Asymmetrical (out of plane) lifts with and without a vertical component have been studied in recent years but researchers have rarely allowed steps to occur during the lifting task (Gagnon et al., 1993). Lifting studies
that allow steps during the lifting motion usually prescribe the exact foot plant locations or the necessary stepping behavior (Delisle et al., 1996; Delisle et al., 1998). Studies in which the placement of the feet is unrestricted are rare (Authier et al., 1996).

Characteristics of representative worker-selected stepping behaviors and foot placements that have not been widely studied are discussed here. The method of using TRACS to quantify novel stepping is also discussed. Limitations of this study and those encountered while applying TRACS to the jobs observed in the automotive assembly plant are discussed in the following.

**Single Limb Ground Contact**

In a large number of the observed MMH transitions, only one foot was in contact with the ground at the time of the transition (e.g., when the object was lifted). The prevalence of this behavior in industrial tasks has also been previously documented by Ljungberg et al. (1989) and Authier et al. (1996). Yet, the important implications toward proactive ergonomics analysis using digital human models regarding this observation have yet to be realized. In our experience, analysts using digital human figure models nearly always posture the figure with two feet in contact with the ground when analyzing pickup or delivery task, and even stances (by the current definition) are much more common than split stances (Stephens et al., 2006). Wegner et al. (2007) in a discussion of future requirements for DHM software highlights the need for more automated methods for posturing manikins to overcome the errors created by analysts using inappropriate postures.

The prevalence of single limb stance pickup and delivery transfers observed in this study may be explained in part by the selection of observed tasks. Negligible to moderately heavy load masses (< 5 kg) predominated the transfer tasks under review. Heavier loads that demand a lifting strategy where a well-established base of support is required might increase the number of behaviors where both feet were in contact with the ground during load manipulation.

The operators under observation were also experienced with the loads being manipulated. Less experienced operators might adopt a more conservative transfer strategy to reduce the risk of a loss of balance and/or injury and maintain both feet in contact with the ground during the terminal stance. Future work should address the
impact of single limb stance on ergonomic analysis and injury prevention as many operators select a single limb stance strategy when lifting and manipulating an object. One potential benefit of the single limb stance strategy may be associated with the capacity to easily change direction directly after the pickup (or delivery). Another potential reason may be attributed to the decrease in energy associated with not having to bring the trailing leg up to a parallel stance to then subsequently have to lift it off the ground when taking the first step in the new direction after the manipulation has occurred. Another reason still, similar to the previous, may be that the operators are incorporating the dynamics of the body movements prior to the pickup to change direction. This strategy can be easily interpreted by considering the whole body supported at the ankle during single support as an inverted pendulum and the associated energy savings occurring during the time the pendulum moves back down after reaching its highest point.

**Terminal Stance Selection**

Stepping behavior terminal stance does not appear to be arbitrarily chosen by the operators. If the terminal stance for the split stance behaviors was arbitrary, the distribution of terminal stances for the split stance cases might be expected to be predominately defined by the position at which the load is encountered during the approaching gait cycle. In this scenario, an equal number of ipsilateral and contralateral lead foot stances would be observed. However, over twice as many contralateral lead foot behaviors were observed than ipsilateral lead foot behaviors. These results imply that operators are actively scaling one or more of their approach steps such that the contralateral limb is placed to facilitate a terminal stance with a contralateral lead foot. This preference might be related to balance maintenance. Consider a three-step transition with an included angle greater than 90°. If the contralateral foot is planted and the ipsilateral foot is being reoriented and repositioned (by definition in the ipsilateral direction), the centre of gravity (defined here as the projection of the centre of mass onto the ground plane) remains within the stability region (Holbein et al., 1997) for the entire movement of the ipsilateral limb (assuming the base of support is defined by the projection of both feet onto the ground. Additionally, when the load is manipulated, the majority of weight of the upper body for a split stance behavior will be over the limb.
closer to the load. If that limb is the ipsilateral foot, a shift in weight must occur to the contralateral limb or an additional step must occur if the balance preference above is to be maintained. For a three-step transition with an included angle less than 90°, maintaining the contralateral limb as the lead foot can be thought of as a continuation of walking with the load manipulation occurring between strides. This interpretation gains support from the third most common behavior, in which the ipsilateral foot is forward (S_cO_lN_bO_cS_t). In this behavior, an extra contralateral preparatory step is inserted immediately after the load pickup to facilitate the weight transfer required to move the ipsilateral foot in the departure direction.

The benefits listed above for a contralateral lead foot stance are not always exploited. Nearly one-quarter of all the observed behaviors maintained the ipsilateral foot as the lead foot during the terminal stance. This result implies either the operators are not always able to scale their approach footsteps such that the contralateral limb is in the lead when load manipulation occurs, or there are additional factors influencing the selection of a terminal stance (and thus a transition behavior). Further study is required in this area to better understand how operators scale their step sizes prior to load manipulation to achieve a desired transition behavior.

**Number of Steps to Turn**

The number of steps to effect a change in direction during a manual material handling transfer task could theoretically be very large, but the majority of transitions in the current study involved three steps. Studies characterizing turning (Hase et al., 1999) or addressing one or a few particular types of turns (Delisle et al., 1996) typically focus on turns in which 2-4 steps are used and the change in direction is limited to a small number of scenarios. The results here support the focus of these researchers on turning behaviors with a small number of steps. The negligible and moderate load weights and the experienced workers encountered in this study may have contributed to the small number of steps during the transitions, which can be interpreted as an efficient strategy. Turning with heavier loads or the adoption of a conservative strategy to minimize the loss of balance may promote transition behaviors with a greater number of steps. The number of steps to perform a 360° turn has been used to distinguish elderly fallers from non-fallers, with the faller population taking six more steps than the non-faller population.
(Lipsitz et al., 1991). Meinhart-Shibata et al. (2005) compared the number of steps associated with self-selected turning strategies of a young and elderly population performing a 180° turning task and found no significant difference in the number of steps. On average, four steps were used to complete the turning task. However, age was reported as a significant factor in the selection of a ‘preparatory strategy’ (defined here as a pivot step) with the elderly population using the pivot step over twice as often (65% of all trials) as the young population. Future work is necessary to quantify the tradeoffs between balance, range of motion, and energy that affected the number and types of steps that workers use during MMH transitions.

**L-TRACS as a Viable Classification System for Stepping Behaviors**

L-TRACS was developed to provide a rigorously defined, general purpose system for describing stepping behaviors for ergonomic applications. L-TRACS was able to classify the wide variety of pickup and delivery transition behaviors observed in the plant study, but L-TRACS is also able to accommodate behaviors with any number of steps. Note that normal gait strides are a particular type of progression step under L-TRACS, so the complete pattern of foot movement associated with a sequence of tasks can be coded. Importantly, L-TRACS includes precise information about the ground contacts in the terminal posture. This information is critical for accurate biomechanical analysis. L-TRACS can be used to group similar stepping patterns through terminal stance, number of steps, progression of steps, or terminal ground contact state. One such grouping was presented that was motivated by the limitations of the video-based observations.

L-TRACS is a categorical system for identifying and defining stepping behaviors, but L-TRACS alone is not sufficient to reproduce all of the important features of a particular stepping pattern. Additional information is necessary to scale an L-TRACS behavior to be used in an ergonomic application with a human figure model (Reed et al., 2007). However, the complexity and high degree of variability of possible transition stepping behaviors have been impediments toward previous efforts of defining a language for turning behaviors being widely accepted. L-TRACS attempts to address many of these issues as a methodology for defining each step and terminal stance for transition behaviors. An integrated system known as Q-TRACS (Quantitative Transition
Classification System) defines the additional information required to fully describe foot motions in non-stationary standing work (Wagner et al., 2006).

One potential limitation of the nomenclature, as defined, is that the qualitative step types suggest that one foot always be in contact with the ground, or rather the proposed nomenclature has no way to distinguish when this is not the case). For example, if this nomenclature were applied to an individual running, where there exists a significant ‘flight’ phase in which both feet are not in contact with the ground, the best approximation with the available step types would be a sequence of progression steps. However, common observation would suggest there exists a substantial difference between a nominal gait stride and one taken during running, although a running step would satisfy all the criteria set forth for a progression step as defined above. However, this limitation in the proposed vocabulary does not affect the analysis presented here as the operators in the assembly plant were always observed with at least one foot in contact with the ground.

Study limitations

Discrepancies between raters for the manipulator hand and turn direction may be in part attributed to the quality of the video. Safety requirements of video personnel prohibited whole body views of the operator at all times during each transition. Raters were asked to identify elements to the best of their ability and apply a ‘null’ element value if the video quality was insufficient to properly identify an element. For example, when identifying the hand used during the manipulation, one rater used the ‘null’ element 41 out of the possible 529 times while another rater was unable to identify only 21 of the same tasks. Differing interpretations of ‘sufficient’ are one possible reason for the discrepancies in these nominal values traditionally easy to classify. The quality of the video limited the correct identification of the ground contact elements for the terminal stance leading to discrepancies between raters when differentiating between toe-contact and no contact situations. The small number of raters also limits the robustness of the inter-rater reliability measures.

Task selection was not arbitrary in this study, which limits the applicability of these results when comparing within or across industries. Jobs were selected based on the prevalence of open space in the work zone biasing the frequency of transfer tasks per
job presented here compared to that of across the entire assembly plant. The limited range of load weights that were manipulated also limits the applicability of applying the observed stepping behaviors to situations where the manipulation of heavy loads may require stepping behaviors not selected here. The results presented here are primarily applicable to lifting MMH scenarios. The stepping behaviors and frequency of occurrences observed during MMH tasks involving pushing or pulling or the use of lift assist devices may be different than the ones presented here. However, the methodologies and the Transition Stepping and Classification System (TRACS) for classifying stepping behaviors would still apply.

2.6. Summary

A methodology for classifying stepping behaviors that includes gait locomotion as a special case was developed and applied to identify worker behavior in an automobile assembly plant. L-TRACS provides a standardized vocabulary for describing task-oriented stepping behaviors. Over 90 percent of the observed patterns of foot movement could be classified by five L-TRACS behaviors. Unexpectedly, the most common terminal posture for pickup or delivery of an object included only one foot in contact with the ground. Contralateral forward foot terminal stance accounted for half the observed terminal stances with ipsilateral (21% of all transfers) and even (29% of all transfers) stance strategies accounting for the remaining postures. The results of this study emphasize the importance of developing accurate methods for simulating foot movement behaviors for proactive ergonomic analysis of industrial tasks using digital human models.

2.7. Appendix A: Glossary

Behavior (Transition Stepping Behavior) – The sequence of non-cyclical steps preceding and succeeding the terminal stance during a lifting MMH event

Contralateral – In relation to the opposite side of a defined direction or body part. E.g. for a turn in the left direction (counter clockwise rotation of the pelvis), the right hand may be referred to as the contralateral hand.

Foot Event – The change in contact state with the ground for the toe or heel. The four types of step events are:
1. Heel Contact (HC)
2. Toe Contact (TC)
3. Heel Lift (HL)
4. Toe Lift (TL)

Contact events are defined as the transition from a non-contact to contact state with the ground. Lifts are defined as the transition from a contact to non-contact state with the ground.

_Ipsilateral_ – In relation to the same side of a defined direction or body part. E.g. for a turn in the left direction (counter clockwise rotation of the pelvis), the left hand may be referred to as the ipsilateral hand).

_Lexical Transition Classification System (L-TRACS)_ – Categorical representation of a Transition Stepping Behavior. The type of each step and the terminal stance are represented. Steps are coded as two-character elements representing the type of step and the foot it is associated with. The terminal stance is coded as a three-character element representing the stance and ground contact state for each foot when the load is manipulated.

_Lifting Manual Material-Handling Event_ – A special case of a Manual Material-Handling Event only involving lifting manipulations. Lifting MMH events are signified by a change in the downward force applied to the manipulator’s hands caused when the load transitions from the hand(s) to the worksite and vice versa. An example of a Lifting MMH event is observed when a load is picked up or delivered.

_Manual Material-Handling (MMH) Event_ – The instance when a part, tool, load, or other object is manipulated by the worker. Manipulation includes, but is not limited to, the following types of external forces: push, pull, lift, and rotate.

_Non-Cyclical (or Acyclical) Stepping_ – A sequence of steps that cannot be characterized by a repeating cycle. The final state of the lower extremities for a non-cyclical stepping progression is usually dissimilar from the initial state.
Non-Stationary Standing Work (NSSW) – A subset of standing work that includes tasks requiring the motion of the lower extremities. NSSW includes jobs requiring locomotion and/or non-cyclical stepping.

Step – The progression of at most four unique foot events. A step is defined by the following:

1. Must contain at least one heel contact (HC) or or toe contact (TC) foot event (see Foot Event definition).
2. Must contain no more than four foot events.
3. Must contain no duplicate foot event.
4. The preceding step of the same foot must contain a TL or HL for each TC or HC contained within the current step respectively.
5. If a Heel or Toe contact foot event occurs, the next Heel or Toe foot event must be a lift respectively. The contact and lift do not need to occur in the same step.

Quantitative Transition Classification System (Q-TRACS) – Quantitative parameterization of a Transition Stepping Behavior. All the steps in each behavior are represented with a position, angle, leg, and four foot event times. All parameter values are referenced to the manipulation location, time, and turn direction (Wagner et al., 2006)

Stationary Standing Work (SSW) – A subset of standing work that includes tasks where no locomotion between workstations is required. SSW requires no steps to be taken throughout the job cycle.

Standing Work (SW) – The combination of stationary and non-stationary standing work (SSW & NSSW). An example of standing work is seen in many work-cell environments where work performed at a single workstation (SSW) is combined with parts retrieval at a central location (NSSW).

Transition Classification System (TRACS) – A method for describing and quantifying Transition Stepping Behaviors. Lexical and Quantitative Transition Classification sub-systems define the descriptive and quantitative representations to facilitate behavior selection and scaling respectively.
Transition Stepping – A subset of non-cyclical stepping; consisting of a set of behaviors used to enact a change of direction during a Lifting Manual Material Handling Event. Steps involved in Transition Stepping are classified here with the Transition Classification System (TRACS).
2.8. References


moments of the l(5)/s(1) and knee joints. *Clin Biomech (Bristol, Avon)*, 13(7):506–514.


CHAPTER 3
THE EFFECTS OF WORKER AND TASK FACTORS ON FOOT PLACEMENTS IN MANUAL MATERIAL HANDLING TASKS

3.1. Abstract
The effects of lifting task conditions and anthropometric variables on foot placements were studied in a laboratory experiment. Sixteen men and women performed unconstrained object transfers in a minimum of 362 different combinations of turn angle, lifting height, object weight, lifting hand, delivery distance, and transfer type. Five different changes in the direction of progression following the object pickup were used, ranging from 45° to 180°. Three pickup heights scaled to subject stature were tested. Subjects performed pickup and delivery tasks with their left, right, and both hand(s). Light, medium, and heavy object masses for the one and two-handed test conditions of 0.5 kg, 2.27 kg, 4.54 kg, and 1.0 kg, 4.54 kg, 13.61 kg, respectively, were used. Three-dimensional whole-body motions were recorded using an optical retro-reflective marker based camera system. Results disclosed that all of the test variables had statistically significant effects on the patterns and/or scaling of the foot placements. Foot placements chosen by the subjects during transfer tasks appeared to facilitate a change in the whole body direction of progression, in addition to aiding performing the lift. Further analysis revealed that a small number of stepping behavior groups account for the majority of behaviors used. Specifically, five stepping behaviors accounted for 71% of the stepping patterns observed for all the pickup and delivery transfers. Those same behavior groups also accounted for 85% of the object transfers observed in the field study presented in Chapter 2. Additionally, 67% of the terminal stance postures for all the pickup and delivery transfers were performed with only one foot on the ground. Analysis of the most frequently observed behavior revealed the lateral placement of the lead foot during
terminal stance was primarily affected by transfer hand and turn angle ($R^2 = 0.83$ for two handed pickups). Changes in object location height were observed to affect fore-aft terminal stance lead foot placement with higher height manipulations being associated with foot placements farther from the pickup location. Regression models were developed and suggest that the placement and orientation of the terminal stance lead foot is predicted moderately well by subject and task factors ($R^2$ of 0.69, 0.43, and 0.68 for lateral placement, fore-aft placement, and foot orientation, respectively).

### 3.2. Introduction

Stance and foot placement positions with respect to a load being manipulated have been shown to affect one’s posture. Subsequently, the results obtained from postural analysis for manual material handling transfer tasks (Bendix et al., 1983; Authier et al., 1996; Delisle et al., 1996; Burgess-Limerick et al., 1998; Delisle et al., 1998; Kollmitzer et al., 2002; Plamondon et al., 2006) depend on stance and foot placements. For proactive ergonomics analyses involving digital human figure models, a whole body posture is required as input to perform any postural or biomechanical analysis. Prediction of the position and orientation of the body end effectors (i.e. hands, feet, and head/gaze) are natural choices for better constraining whole-body models (see Badler et al., 2005; Reed et al., 2006; and the Task Simulation Builder (TSB) Siemens UGS Tecnomatix Jack for examples of these constraints). This may be one potential reason many of the currently available posture prediction models require the users to specify foot locations or stance with respect to the load. For pickup and delivery tasks in particular, the hands and gaze are traditionally constrained to the part or fixture being manipulated, and may not change significantly over the feasible range of postures. Unfortunately, the feet are not as well constrained, and guidelines for predicting appropriate foot positions are not as well defined (Delisle et al., 1999; Kollmitzer et al., 2002).

Much of the research involving foot placements related to postural lifting analysis has focused on lifting capability, and not lifting preference. For example, the capacity to maintain balance while holding different weights in varied positions and stances has been studied (Holbein et al., 1997a; Holbein et al., 1997b; Lee et al., 2003). Wu et al., 2001 investigated the effects on whole body center of mass when a weight was asymmetrically loaded on the right side of the body while stance width was varied. Gillete et al. (2003)
demonstrated more consistent Center of Pressure (COP) excursions across different reach directions for split stance postures as compared with parallel stance postures. The individual effects pertaining to lifting height, object weight, trajectory, and lifting speed on peak dynamic L5/S1 moments have been investigated for: sagittal plane lifts utilizing parallel stance (Buseck et al., 1988; Tsuang et al., 1992; Lavender et al., 2003), asymmetric lifts utilizing parallel stance (Plamondon et al., 1995; Hooper et al., 1998), and asymmetric lifts over varied stance widths (Authier et al., 1995; Delisle et al., 1998) to name a few. Although very applicable for assessing the lifting techniques as they were defined, these types of studies are not useful for predicting how people will perform tasks that include minimal constraints on foot placements.

Unfortunately the posture and motion prediction models currently available for predicting MMH lifting tasks tend to be highly specific toward a particular lifting task or technique and require as input an initial posture or relative position to the load (Ayoub, 1995; Dysart et al., 1996; Hsiang et al., 1997; Ayoub et al. 1998; Chang et al., 2001; Gundogdu et al., 2005). Interestingly, none of the posture prediction models reviewed were designed to predict stance or relative foot placements, even though in a comparison of novice and experienced lifters, foot placement was shown to be a significant factor (Authier et al., 1996). One potential reason for this limitation may be attributed to the methods used for predicting the remaining body posture not being well suited for realistically simulating foot placements during lifting tasks. For example, models in which whole body balance is optimized (Dysart et al., 1996; Hsiang et al., 1997), may not be able to adequately reflect the observation that experienced handlers seldom stood on both feet, but supported their body weight on a single foot throughout the lift (Ljungbert et al., 1989; Authier et al., 1996). Another popular posture prediction modeling technique uses a minimization criterion of the net torque over a set of joints (i.e. a minimum exertion hypothesis) to find a solution to the redundant degrees of freedom of the whole body model (Ayoub et al., 1995; Dysart et al., 1996; Hsiang et al., 1997; Ayoub et al., 1998; Chang et al., 2001). However, this modeling methodology may be contradicted by the lack of acceptance in select training programs that promoted similar handling techniques (Chaffin et al. 1986; Harber et al., 1988; Kroemer, 1992). In particular, this discrepancy has been observed for lifts being performed not limited to
only the sagittal plane (St-Vincent et al., 1989) in which the recommended technique was intended to reduce one or a multiple set of internal joint forces and/or moments. Additional studies have also reported experienced workers using lifting techniques other than the ones recommended (Drury et al., 1982; Baril-Gingras et al., 1995; Kuorinka et al., 1994).

Another potential limitation to the previously cited lifting studies is the relatively small distance between the operator’s starting location, the pickup location, and the delivery location. In a review of 944 handling transfers in a distribution center for a large transport company, Baril-Gingral et al. (1995) reported that workers took two or more steps in over half of the transfers (57%). However, few previous studies performed have included pickup or delivery tasks separated by more than two steps. Delisle et al. (1999) analyzes four stepping strategies involving multiple steps, however the experiment participants were instructed on the strategy to use. Authier et al. (1996) analyzed operator-selected transfer techniques of expert material handlers and allowed the participants to take as many steps as was preferred. The interpretation of the results suggested that positioning of the feet could be a significant determinant in how the lift was executed. Additionally, the results also suggest that movement prior to the actual lift (i.e. walking up to the object being lifted), may significantly affect the foot placements (and potentially technique) and subsequently the posture and/or movement during the lift.

An extremely large variety of stepping patterns (defined by the number of steps and their placement) are theoretically possible for people performing an object pickup or delivery task. However, the results from Chapter 2 suggest that only a small number of stepping behaviors are used by experienced operators to accomplish the majority of manual material handling transfer tasks encountered in a work-cell environment. The study presented here investigates the effects of selected task and operator characteristics on five of the most commonly observed stepping patterns. Additionally, the terminal stance (i.e. relative foot positions at the times of grasp or release of the object) and the ground contact state of each foot during the terminal stance are also investigated. Individual and interactive effects of the task and operator characteristics on the foot positions and orientations of the most common stepping behavior are discussed. Based
on the field observations described in Chapter 2 and the literature reviewed, the following hypotheses were used to guide the study:

- Step behavior selection is significantly affected by task criteria, (tested by the null hypothesis that behavior selection is independent of the transfer task variables).
- The effect of handedness (ipsilateral, both, and contralateral) on the lateral placement of the terminal stance lead foot is linear with ipsilateral-handed transfers (defined by the direction of turn) associated with the most contralateral deviations and contralateral-handed transfers associated with the most ipsilateral deviations.
- The effect of turn angle on foot placement is not significant if the foot positions are measured with respect to the approach and departure direction of progressions from which the turn angle is defined.
- The fore-aft distance between the terminal stance lead foot and the location of the transfer object is proportional to the mass of the object.
- A non-linear relationship exists between the object height and the fore-aft position of the lead foot such that the low and high shelf manipulations result in a greater lead foot distance from load than the middle shelf transfers.
- The effects of transfer hand, object weight, object height, and turn angle independently affect foot placement and orientation during a transfer task.

3.3. Methods

Participants moved boxes and cylindrical objects with a range of weights between pickup and delivery locations while their whole-body motions were recorded. Testing was conducted with low, middle, and high pickup and delivery shelves scaled to participant stature. By varying the tower and participant start locations, the approach and delivery azimuths and delivery distances were varied. Delivery tower and start location distance to the pickup tower were scaled to two nominal step transition distances measured during the preliminary trials (the definition of those scaling values is described in detail later). Figure 3.1 shows a participant in the test facility.
Subjects

Motion capture data were obtained from a total of sixteen paid participants as part of a larger experiment. Subjects were recruited by word of mouth and solicited via public posting. Subjects were required to have no previous history of any musculoskeletal disorder or recurring low back pain. Subjects were also required to be right handed. Table 3.1 presents a summary of the anthropometry and other relevant attributes for each participant. Population strength percentiles are calculated based on data presented by Chaffin et al., 1999 and with assumed distributions as presented by Keyserling, 1979. The numbering scheme for each subject is retained from the larger experiment for clarity between studies. Participants performed the same number and conditions of pickup and delivery transfers with the exception of Subject’s 1 and 4, who also performed additional trials. This difference in the number of conditions is identified in Table 3.1 by the experiment group heading (I_A for subjects 1 and 4, I_B for the remaining subjects). Summary statistics for the participants of both experiment groups I_A and I_B are presented together as those data collected for trial group I_B are a subset of the conditions collected for set I_A and evaluated together in this chapter. The combined data are referred to as I_A+B from this point forward.

Data for the I_A+B group were obtained from 8 male and 8 female paid participants: mean [SD]: age: 20.5 [1.2] years and 22.9 [4.5] years; stature: 181.5 [9.9] cm and 168.1
The participants ranged from 17\% tile to 99\% tile by stature for the male subjects and 31\% tile to 99\% tile by stature for the female subjects (Roebuck, 1995). The protocol was approved by an institutional review board, and all participants provided written, informed consent.

Table 3.1. Summary information for experiment participants.

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<th>Participant Number</th>
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<th>Gender</th>
<th>Age (years)</th>
<th>Stature (cm)</th>
<th>Body Mass (kg)</th>
<th>Body Mass Index (kg/m$^2$)</th>
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<th>25% tile Torso Lift</th>
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Facilities

A six-camera Qualisys Proreflex 240-MCU (Qualisys, Sweden) passive optical motion tracking system was used to capture kinematic data of human movement within a 3.6 x 4.8 m floor area. Kinematic data were sampled at 50 Hz. Foot switches affixed to the ball and heel of the foot inside the shoe of the participant were used to collect heel and toe ground contact times. Two AMTI force plates were used near the pickup and delivery towers for a subset of trials to quantify balance related issues during those transfer phases. Pressure switches on each shelf were sampled to determine the time of pickup and delivery. All analog signals were sampled at 500 Hz.

Twenty-nine 25-mm-diameter retro-reflective markers were affixed to each participant to track whole body motion (Figure 3.2). Additionally, 25 body landmarks were manually digitized prior to testing to track those positions as locally fixed points (when possible) in associated local coordinate frames defined by 3 or more reflective markers. For example, the left and right anterior superior iliac spine (ASIS) body
landmarks on the pelvis were tracked during the experiment by (1) palpating along the front of the pelvis to determine their location; (2) digitizing those points with respect to the four reflective markers that were affixed to the posterior side of the pelvis near the left and right posterior superior iliac spine (PSIS) bony landmarks (two markers each); and (3), by using the measured locations of the pelvis markers during trials to compute the ASIS locations. Joint center locations were calculated from body landmark and marker locations using a method similar to that described by Reed et al. (1999). The calculated whole body linkage was used to define the positions and orientations of the feet during ground contact. The linkage was also used to calculate the locations of the hands and pelvis during the object pickup and delivery and at the start and end of each trial.

Test Conditions

For each trial in the experiment $I_{AB}$, the participant moved one hand (cylindrical) and two hand (totes) objects from one location to another. Each trial is defined by eight
variables: transfer type, approach angle, departure angle, delivery distance, lifting hand(s), object weight, lifting height, and delivery height. Participants in the I_A and I_B trial groups were asked to perform a total of 202 and 181 trials, respectively, in which both a pickup and delivery were recorded. A representative trial is shown in Figure 3.3. Participants were asked to approach a load on a shelf from 3-4 steps away, pick up the load, transfer it to another shelf 1-5 steps away, and return to the initial start position.

![Figure 3.3. Participant performing a pickup and delivery transfer trial (1-6). Participant is 1) at the start location waiting to begin, 2) approaching pickup tower, 3) picking up the load, 4) carrying load to delivery tower, 5) delivering the load, 6) returning to the start location.](image)

The start and shelf tower locations and the associated one and two-handed conditions for each configuration are graphically depicted in Figure 3.4. One-handed conditions include left and right-handed transfers. Three one-handed and three two-handed loads were tested. Cylinders with a diameter of 7.62 cm were used for the one-handed loads. The two-hand tote had horizontal cylindrical handles with diameters of 3.81 cm. The light, medium, and heavy one-handed loads were 0.50, 2.27, and 4.54 kg. The two-handed loads were 1.0, 4.54, and 13.61 kg respectively. The 2.27 kg (5 lbs), 4.54 kg (10lbs), and the 13.61 kg (30 lbs) loads were selected for comparison to objects in industrial work cells, similar to those observed in Chapter 2. The light load conditions were constructed and matched (two handed load being twice as much as the one handed object) to provide a ‘no-weight’ condition similar to those objects defined as negligible weight in Chapter 2. The shape and color of each object was such that each hand/load combination could be uniquely identified visually (Figure 3.5). The one-handed cylinder
objects were always placed on-end as depicted in Figure 3.5 and participants were instructed to carry them with a similar orientation. Medium one-handed and two-handed weights were transferred between the middle pickup and delivery shelves for all the configurations shown in Figure 3.4.

Figure 3.4. Experiment start and delivery conditions. Distances are not drawn to scale. Delivery distances for each trial condition are labeled using the abbreviated nomenclature presented in Table 3.3.
Light and heavy load weight and low and high shelf height conditions were chosen to investigate pickup and delivery height and load weight effects. Low, middle, and high pickup and delivery shelf heights were scaled to 0.15, 0.53, and 0.9 times subject stature. For low and middle shelf pickup and deliveries, the higher shelves were raised to avoid interference with the transfer motion. Test conditions were blocked within tower configuration to facilitate timely data collection and trials were randomly assigned within each block. Table 3.2 categorizes the trial conditions for each experiment group. Each row in Table 3.2, (referred from here forward as a trial set), corresponds to a full factorial set of trial conditions used for the associated experiment group unless otherwise stated.

Trials for each experiment group were blocked on trial set and randomly presented to the participant. Within each trial set, the trials were again blocked on pickup and delivery shelf height to facilitate data collection in a timely fashion. Randomization of trials occurred within and between block sets for each participant.
Table 3.2. Trial conditions for the experiment groups $I_A$ and $I_B$.

<table>
<thead>
<tr>
<th>Number of Trials</th>
<th>Approach Angle*</th>
<th>Departure Angle*</th>
<th>Delivery Distance†</th>
<th>Lifting Hand(s)</th>
<th>Object Weight</th>
<th>Lifting Height</th>
<th>Delivery Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>+135 180 -135</td>
<td>+135</td>
<td>5$p^4$</td>
<td>Right Left Both</td>
<td>Light</td>
<td>Medium</td>
<td>Low Middle High</td>
</tr>
<tr>
<td>27</td>
<td>180 +135</td>
<td>5$p^4$</td>
<td>Right Left Both</td>
<td>Light Medium Heavy</td>
<td>Middle</td>
<td>Low Middle High</td>
<td></td>
</tr>
<tr>
<td>$I_A$ 36</td>
<td>180 +135</td>
<td>$a_1$, $a_2$, ..., $a_{12}$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31**</td>
<td>+135 180 -135</td>
<td>5$p^3$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>+135 180 -135</td>
<td>+90</td>
<td>$s_1$, $s_2$, $s_3$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
</tr>
<tr>
<td>81‡</td>
<td>+135 180 -135</td>
<td>+135</td>
<td>5$p^4$</td>
<td>Right Left Both</td>
<td>Light Medium High</td>
<td>Low Middle High</td>
<td></td>
</tr>
<tr>
<td>$I_B$ 18</td>
<td>180 +135</td>
<td>$b_1$, $b_2$, ..., $b_6$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24**</td>
<td>+135 180 -135</td>
<td>5$p^3$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>+135 180 -135</td>
<td>+90</td>
<td>$s_1$, $s_2$, $s_3$</td>
<td>Right Left Both</td>
<td>Medium Middle Middle</td>
<td>Middle</td>
<td></td>
</tr>
</tbody>
</table>

* Angles are defined by shelf orientation; see Figure 3.6 for a definition of the angle system used here.
† Distances are scaled from step lengths taken from preliminary trials (see procedures section), see Table 3.3 for an explanation of the abbreviations used here.
** Redundant one handed trial conditions that yielded the same included angle between the approach and departure angles were excluded.
‡ For the -135° approach angle subset, low, middle and high delivery shelves were used as opposed to all other trials in which only the middle delivery shelf was used.
Table 3.3. Abbreviations used for the delivery distance trial conditions*.

<table>
<thead>
<tr>
<th>Abbreviated Nomenclature</th>
<th>Condition Description†</th>
</tr>
</thead>
<tbody>
<tr>
<td>5p3</td>
<td>Location defined by the midpoint between the shelf locations for which the 2-3 step transition and 3-4 step transition occurs.</td>
</tr>
<tr>
<td>5p4</td>
<td>Location defined by the midpoint between the shelf locations for which the 3-4 step transition and 4-5 step transition occurs.</td>
</tr>
<tr>
<td>a1, a2, ..., a12</td>
<td>Twelve uniformly spaced positions between the shelf locations for which the 1-2 step transition and 4-5 step transition occurs</td>
</tr>
<tr>
<td>b1, b2, ..., b6</td>
<td>Six uniformly spaced positions between the shelf locations for which the 1-2 step transition and 4-5 step transition occurs</td>
</tr>
<tr>
<td>s1, s2, s3</td>
<td>Fixed distances of 0.6, 1.2, and 1.8 meters</td>
</tr>
</tbody>
</table>

* See procedure section for a more detailed description of how these distances were measured
† All reference delivery distances are defined for a two handed, medium load transfer between middle shelves with an approach and departure angle of 0° and +135°, respectively.

Figure 3.6. Definition of angle system used for defining the approach and departure angles.

Procedures

Participants for each experiment group attended two data collection sessions. The two sessions were always on different days. During the first session, participants were introduced to the equipment being used, had their anthropometry recorded, performed three isometric strength testing exertions (described in detail later) for three repetitions, and practiced the load transfer protocol to be used during the second session. During the load transfer practice, which lasted approximately 45 minutes, the participant became familiar with each hand/load combination and was specifically instructed that the weight and configuration of the loads they handled would be the same during the next session.
Furthermore, the participant was informed that at no time during the experiment would the load weights be changed.

During the practice load transfer session with the following experiment configuration: approach angle of 180°, departure angle of +135°, medium weight two handed object, and pickup and delivery height - middle shelf; the delivery distance was varied by the experimenter to find the shelf locations that corresponded to the participant transitioning from 0-1, 1-2, 2-3, 3-4, and 4-5 steps to complete the transfer. Those step transitions were recorded and used to scale the approach and delivery distances for the second session to normalize the transfer distances across subjects to self-selected values defined by number of steps. Specifically, the midpoint between the shelf locations for the 2-3 and 3-4 step transitions (\(5p3\) in Table 3.3) and the midpoint between the shelf locations for the 3-4 and 4-5 step transitions (\(5p4\) in Table 3.3) were used to scale subject start, subject end, and shelf locations. In addition to recording the step transitions for the two handed medium load along a departure angle of +135°, the participants also practiced transfers with all the hand/load weight combinations. The first session lasted approximately 2 hours for each participant.

The second session consisted primarily of object transfers in which the participant’s whole body motion was recorded. The subjects were instructed to not perform any potentially fatiguing activity the day before participating in the second session (example activities of rock climbing and long distance running were given). At the beginning and end of the second session, three isometric maximum strength exertions (squat lift, back lift, and arm lift) repeated 3 times each, were conducted and compared with the respective strength exertions observed during the first session as a measure of fatigue assessment (Chaffin et al., 2006). No significant differences between the maximum strength exertions were observed for any of the subjects between sessions. Following the strength exertions, 29 retro-reflective markers were affixed to the participant (Figure 3.2) and the subject was asked to perform three range-of-motion trials lasting 20 seconds each to aid in the subsequent automatic identification of the optical markers following the data collection period. After the range-of-motion trials, the 25 digitized points (body landmarks) were captured.
The second session lasted approximately 5 hours. Each MMH transfer trial lasted 12 seconds. Prior to each trial, the participant was instructed to stand at a prescribed start location marked by a piece of tape on the floor. The subjects were then instructed which hand to use for the lift (for single handed lifts) and reminded of the object weight (light, medium, or heavy). The subjects were allowed to practice the transfer prior to data collection if they requested. An LED light placed near the pickup tower was used as a signal for the subject to begin the transfer trial. Following the pickup and delivery, the participant was instructed to return to the start location facing the same direction as at the beginning of the trial until the LED light signaled the trial was completed. Trials in which the subject used the incorrect hand or did not return to the correct start location were discarded and the test condition was repeated.

**Quantitative Transition Stepping Classification (Q-TRACS)**

Each stepping strategy performed by each subject was classified using L-TRACS as previously defined in Chapter 2. Additionally, each foot behavior was quantitatively defined by Q-TRACS (Quantitative Transition Stepping Classification). For each foot behavior, Q-TRACS defines a unique set of relative foot positions and timed foot events (heel contact, toe contact, heel lift, and toe lift). A footstep in TRACS describes the contact of a foot with the floor, the stance interval, and the departure of the foot from the floor. Eight parameters, defined below in the vector $F$, are used to represent each step. Vector $F$ is given by:

$$F = [f, T_x, T_y, \theta, t_{hc}, t_{tc}, t_{hl}, t_{tl}]$$

where $f$ is the foot (right or left); $T_x, T_y$ is the location of the foot origin, $\theta$ is the orientation of the foot; and the $t_{nn}$ are the times of the heel contact, toe contact, heel lift, and toe lift events.

Movement is represented as a sequence of steps defined by a step matrix

$$S = [F_1, F_2, \ldots, F_n]^T$$

where $n$ is the number of steps in the movement. $S$ can be partitioned into right and left-foot components,

$$S = [S_R, S_L]$$

The sequence of $F$ in $S_n$ is temporal, such that all $t_i$ in $F_j$ are strictly less than any $t_i$ in $F_{j+1}$. 

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The definition of $F$ is also facilitated by a parameterization, which defines the positions and orientations of each foot with respect to a direction of progression vector. Different steps in the step matrix $S$ (sequence of steps) can be defined relative to a different direction of progression. Huxham (2005) proposed a similar method for defining selected spatial parameters for non-linear walking. An example in which a manual material handling transfer task occurs is graphically depicted in Figure 3.7.A. The first two steps in the Figure are referenced with respect to the approach vector (direction of progression prior to transfer) and the final step is referenced with respect to the departure vector (direction of progression after the transfer is completed).

Data Analysis

An 18-segment kinematic linkage consisting of 39 joint centers and anatomical landmarks was constructed from the digitized body landmarks and reflective marker data (Figure 3.8). All kinematic variables presented here are derived from that linkage. The relationship between the sequence of steps (defined in Chapter 2 as the transition behavior) and the independent and anthropometric variables previously defined are investigated using contingency analysis. Transition behaviors were automatically identified using a computer algorithm implementing the step criteria described in Chapter 2. The state of each foot (Figure 3.9) at every time step was identified using the footswitch data and used to define the terminal stance at each pickup and delivery. Foot placement and orientation (defined by the projection of the ball of foot and ankle joint onto the ground plane) for the most frequently observed transition behavior are investigated (Figure 3.7.A). Each foot position is parameterized by 3 variables: lateral position ($X_i$), fore-aft position ($Y_i$), and orientation ($q$). Foot positions are defined in one of two reference frames, the approach or departure. Both reference frames are defined by the direction of progression prior to (approach frame) and following (departure frame) the manipulation. The approach direction of progression is calculated here as the vector (in the ground plane) defined by the initial pelvis location (Wagner et al., 2006) at the beginning of the trial and the pickup manipulation location. The departure direction of progression was calculated as the vector (in the ground plane) defined by the pelvis location at the pickup and the delivery manipulation location. Equivalent locations were used to define similar vectors for the associated delivery reference frames. Each
manipulation location was calculated as the location of the handgrip center (one-handed transfers) or the average of the grip centers (two-handed transfers) at the instance the load was transferred (measured by the change in state of the pressure switch located on the pickup and delivery shelves). Lead foot placement and orientation (for split-stance behaviors), the midpoint position between the feet (for parallel-stance behaviors), and the relative step length, step width, and step orientation measured with respect to the direction of progression for all the steps included in the behavior are investigated. Figure 3.7 shows an example Q-TRACS parameterization for a representative (A) split stance and (B) parallel stance behavior. The reference frames (approach and departure) for both conditions are offset along the respective direction of progressions for clarity in the figure, however both frames are collocated and share an origin at the manipulation location.

The effects of turn angle, object weight, object position, and lifting hand on the foot positions are only presented for the most commonly observed stepping behavior for clarity. Specifically, the effects of each of the task factors on each of the nine variables used to parameterize that behavior are discussed. Similar analysis was performed for the other commonly observed behaviors and those results are presented in Chapter 4. A summary of the independent and dependent measures investigated here is presented in Table 3.4.
Figure 3.7. Parameterization of a representative (A) split stance and (B) parallel stance transition behavior.
Figure 3.8. Kinematic linkage used for data analysis constructed from digitize landmarks and reflective marker positions. Used to compute foot, hand, and pelvis locations throughout each trial.

Figure 3.9. Four parameterized ground contact foot states.
Table 3.4. Summary of analyses, grouped by hypothesis and associated control and dependent variables.

<table>
<thead>
<tr>
<th>Hypothesis (abbrev.)</th>
<th>Control Variables</th>
<th>Dependent Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step behavior preference is not significantly affected by task criteria</td>
<td>Turn Angle*</td>
<td>† Transition Behavior Group (see chapter 2 for detailed description):</td>
</tr>
<tr>
<td></td>
<td>Object Height</td>
<td>S_{O_1C_1B_1S_1}</td>
</tr>
<tr>
<td></td>
<td>Object Weight</td>
<td>S_{O_2C_2B_2O_2S_2}</td>
</tr>
<tr>
<td></td>
<td>Transfer Hand(s)</td>
<td>S_{O_3J_3B_3O_3S_3}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S_{O_4E_4B_4O_4S_4}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S_{O_5J_5B_5S_5}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>There exists a symmetric relationship between the hand(s) used to perform the transfer and the lateral position of the lead foot.</td>
<td>Transfer Hand(s)</td>
<td>For the S_{O_1C_1B_1S_1} transition behavior:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X_1</td>
</tr>
<tr>
<td>The variance in the foot positions associated with turn angle is not significant when the foot placements are measured with respect to the approach and departure direction of progressions from which the turn angle is defined.</td>
<td>Turn Angle Transfer Hand(s)</td>
<td>For the S_{O_2C_2B_2O_2S_2} transition behavior:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 1 (S_{1}): X_1, Y_1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 2 (O_{2}): X_2, Y_2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 3 (S_{3}): X_3, Y_3</td>
</tr>
<tr>
<td>The fore-aft distance between the terminal stance lead foot and the location of the transfer object is proportional to the mass of the object.</td>
<td>Object Weight Transfer Hand(s)</td>
<td>For the S_{O_3C_3B_3S_3} transition behavior:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y_2</td>
</tr>
<tr>
<td>A non-linear relationship exists between the object height and the fore-aft position of the lead foot such that the low and high shelf manipulations result in a greater lead foot distance from load than the middle shelf transfers.</td>
<td>Object Height Transfer Hand(s)</td>
<td>For the S_{O_4C_4B_4S_4} transition behavior:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y_2</td>
</tr>
<tr>
<td>The effects of transfer hand, object weight, object height, and turn angle independently affect foot placement and orientation during a transfer task.</td>
<td>Turn Angle Object Height Object Weight Transfer Hand(s)</td>
<td>For the S_{O_5C_5B_5S_5} transition behavior:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 1 (S_{1}): X_1, Y_1, q_1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 2 (O_{2}): X_2, Y_2, q_2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step 3 (S_{3}): X_3, Y_3, q_3</td>
</tr>
</tbody>
</table>

* Turn Angle is defined as the rotational difference between the approach and departure frames.
† See Table 3.5 for a summary description of the L-TRACS nomenclature for each behavior.

3.4. Transition Behavior Results

Behaviors Distribution

The results from Chapter 2 suggest that a small number of stepping behaviors are used to accomplish a large range of work cell tasks. In an effort to present the most comprehensive analyses and yet maintain a broad range of applicability for the results, interpretations of the effects of task and anthropometric factors on foot placements is presented for a subset of the observed stepping behaviors. Five stepping behavior groups (Table 3.5) are included in analyses presented here. Four of the behavior groups correspond to the most frequently observed stepping patterns from the laboratory experiment presented here. The remaining behavior group is included as a special case primarily observed when the turning angle is negligible or selected to maintain balance.
by utilizing a compensatory step. A similar distribution of transition behaviors was observed in Chapter 2 in a review of the stepping patterns used by assembly operators during manual material handling tasks in an automotive assembly plant (Figure 3.10). In the assembly plant observations, the 7 most frequently observed behavior groups accounted for over 90% of the 529 documented material handling transfers. For consistency of presentation between the two studies, the behavior groups from the laboratory study that differ only by the sequence of steps prior to the terminal stance were grouped. The additional grouping was necessary to accurately compare the two studies, as the assembly plant observations could not distinguish among those behavior groups. Table 3.5 describes the nomenclature (repeated from Chapter 2) used to describe each stepping behavior group. References in the text to each behavior group are made using the L-TRACS code or the short name for clarity. The five selected behavior groups are defined from the laboratory study account for over 85% of the observed behavior groups from the assembly plant observations (Figure 3.11).

Each behavior group is comprised of a set of transition behaviors (as defined in Chapter 2) with the following common attributes:

1. Number of steps
2. Lead foot during the terminal stance
3. Sequence of steps
Table 3.5. L-TRACS Behavior Group Descriptions. Refer to Chapter 2 for a more detailed description of the L-TRACS codes

<table>
<thead>
<tr>
<th>Behavior Number (Order of Prevalence)</th>
<th>L-TRACS Codes*</th>
<th>Stance</th>
<th>Number of Departure Steps</th>
<th>Description</th>
<th>Short Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(S_0O_1C_{bb}S_1)</td>
<td>Contralateral Foot Forward</td>
<td>1</td>
<td>Split stance, contralateral foot forward, depart with an ipsilateral progression step</td>
<td>One-Step</td>
</tr>
<tr>
<td>2</td>
<td>(S_0O_1C_{bb}O_1S_1)</td>
<td>Contralateral Foot Forward</td>
<td>2</td>
<td>Split stance, contralateral foot forward, depart with an ipsilateral orient step followed by a contralateral progression step.</td>
<td>Two-Step</td>
</tr>
<tr>
<td>3</td>
<td>(S_0I_{bb}O_1S_1)</td>
<td>Ipsilateral Foot Forward</td>
<td>2</td>
<td>Split stance, ipsilateral foot forward, depart with contralateral foot orient step, followed by ipsilateral progression step.</td>
<td>Ipsilateral Two-Step</td>
</tr>
<tr>
<td>4†</td>
<td>(S_0O_1E_{bb}S_1) (S_0O_1E_{bb}S_1) (S_0I_{bb}S_1) (S_0I_{bb}S_1)</td>
<td>Even</td>
<td>1</td>
<td>Even stance, approached by either ipsilateral or contralateral foot first depart with a progression step from either step first. (Represented by ipsilateral departure step.)</td>
<td>Even</td>
</tr>
<tr>
<td>5</td>
<td>(S_0O_1I_{bb}S_1)</td>
<td>Ipsilateral Foot Forward</td>
<td>1</td>
<td>Split stance, ipsilateral foot forward, depart with a progression step using the contralateral foot, stepping across the ipsilateral foot.</td>
<td>Crossover</td>
</tr>
</tbody>
</table>

* If more than one behavior is included in the Behavior group, the representative notation is shown in bold.
† Because the approach to an even stance can start with either the ipsilateral or contralateral foot, the subscripts 1 and 2 are used to indicate the first and second foot to arrive at the terminal (even) stance.

Table 3.6. Frequency of transition behaviors observed in the laboratory and field studies

<table>
<thead>
<tr>
<th>Behavior Group (L-TRACS code)</th>
<th>Frequency Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laboratory Study</td>
</tr>
<tr>
<td>(S_0O_1C_{bb}S_1)</td>
<td>38.7</td>
</tr>
<tr>
<td>(S_0O_1C_{bb}O_1S_1)</td>
<td>23.7</td>
</tr>
<tr>
<td>(S_0I_{bb}O_1S_1)</td>
<td>5.1</td>
</tr>
<tr>
<td>(S_0O_1E_{bb}S_1)</td>
<td>2.6</td>
</tr>
<tr>
<td>(S_0O_1E_{bb}S_1)</td>
<td></td>
</tr>
<tr>
<td>(S_0O_1I_{bb}S_1)</td>
<td>1.3</td>
</tr>
<tr>
<td>*(S_0O_1I_{bb}S_1)</td>
<td></td>
</tr>
<tr>
<td>All Listed Behaviors</td>
<td>71.4</td>
</tr>
</tbody>
</table>

* included as a behavior group for negligible turn transfers.
Results of Subject and Task Effects on Transition Behavior Selection

A subset of the pooled $I_{A+B}$ trials was extracted to investigate the influences of task and subject variables on the behavior selection. Laboratory trials in which one of the
top five observed stepping behaviors (Figure 3.11) was selected (2477 of 3485 I_{A+B} trial transfers were analyzed).

For clarity, the two behaviors in which the terminal stance is even (S_{1}O_{c}E_{bb}S_{1} and S_{c}O_{t}E_{bb}S_{t}, which differ only by the last foot to enter the even stance) are treated as equivalent behaviors and referred to in this section as the even (S_{1}O_{c}E_{bb}S_{1}) stance behavior. The effects of turn angle, shelf height (treated here as a nominal variable), handedness, object mass (scaled by body weight), stature, and Body Mass Index (BMI) are investigated. Gender was not observed to have a significant effect on the selection of a particular stepping behavior, and thus trials are pooled across gender for this analysis.

Bivariate mosaic plots depicting the distributions of transfer type, lifting hand(s), and shelf heights associated with the five selected stepping behaviors are shown in Figure 3.12. Marginal homogeneity metrics for each of the nominal test variables were computed. The hypothesis that the response rates for the variable depicted on the y-axis (transfer type for Figure 3.12.A) was the same for each stepping behavior was tested using the Likelihood Ratio Chi-square test. Significant differences (p<0.01) for all of the nominal variables across the different stepping behaviors were observed. This result is not surprising considering the number of behaviors used in the analysis and the relatively weak requirements of the test statistic.

The information presented in the mosaic plots may be more informative toward understanding the potential differences between the individual behaviors with respect to each nominal variable. Additionally, the distribution of the nominal test variable is also presented allowing for a visual comparison between each behavior and the percentage the nominal test variable occurs in the data. For example, Figure 3.12.A suggests that when an even stance (stepping behavior S_{1}O_{c}E_{bb}S_{1}) was performed, it was primarily associated with pickup transfers (72%), about 20% more frequent than pickup transfers occurred overall. However, the one-step (S_{c}O_{c}C_{bb}S_{1}) stepping behavior appears to have no relationship to the type of transfer being performed with approximately the same percent of all delivery transfer S_{1}O_{c}C_{bb}S_{1} trials very similar to the overall percent of delivery transfers observed, 48% and 46% respectively.

The frequency of each lifting hand(s) appears to not be significantly different between four of the five stepping behaviors (Figure 3.12.B). The lone exception is the
ipsilateral two-step \((S_cO_lI_{bb}O_cS_t)\) stepping behavior of which ipsilateral and two-handed lifts appear to be more prevalent. For the same behavior, the percentage of contralateral-handed lifts is approximately 20% lower than the overall average of those lifts in the data.

Shelf height appears to primarily affect the selection of stepping behaviors in two situations. The percentage of low shelf height transfers (42%) is significantly more prevalent than the overall average (14%), and the other stepping behaviors (13% for the other closest behavior), for the even \((S_lO_cE_{bb}S_t)\) stepping behavior. Additionally, the percentage of high shelf transfers for the same behavior (10%) occurred at a comparable frequency to the overall average (13%) suggesting that the selection of this even stance behavior may be comparable to other behaviors for high shelf transfers, but preferred for lower shelf transfers. The relative percentage of high shelf transfers that were performed using the two-step \((S_lO_cC_{bb}O_lS_t)\) stepping behavior (23% versus the overall average of 13%) also suggests an interaction between this behavior and transfer height. A Chi-square value testing the significant difference between the frequencies of high shelf height transfers for this stepping behavior and the mean percentage of occurrence is computed. The Chi-square value of 56.8 suggests that the probability of this relationship occurring by chance alone is \(p<0.01\).
Figure 3.12. Mosaic plots of the most frequently observed stepping behaviors by A) Transfer type, B) Lifting hand(s), and C) Shelf height.

Figure 3.13 depicts the distribution of turn angles associated with each of the stepping behaviors selected here. The Tukey-Kramer HSD test is used to test for a significant difference (p<0.05) between each pairing of stepping behaviors in the average turn angle. The one-step (S₁O₂C₁BB₁S₁), even (S₁O₂S₁BB₁S₁), and ipsilateral two-step (S₁OC₁BB₁O₁S₁) stepping behaviors were observed to not be statistically different in average turn angle with mean values of 118°, 117°, and 124°, respectively. However, the
ipsilateral two-step ($S_C O_I B_O S_I$), stepping behavior was not performed for any turn with an included angle less than 76°, while the other two behaviors were observed to be used for turns ranging from 12° to 197°.

The final stepping behavior, two-step ($S_O C_{BB} O_S S_I$), was associated with significantly larger turn angle transfers than the remaining four behaviors. The average turn angle associated with this behavior was 141°. Additionally, the two-step behavior was observed to be used for the majority of instances the turn angle was greater than 180°, with the one-step ($S_O C_{BB} S_I$) stepping behavior being used for the remaining trials.

![Bivariate plot of the most frequently observed stepping behaviors by turn angle.](image)

The relationships between stepping behavior selection and subject characteristics were examined (Figure 3.14). Using the same Tukey-Kramer HSD test (significance of $p<0.05$) as described above, significant differences between the stepping behaviors were identified based on stature and BMI alone. The average stature associated with the two-step ($S_O C_{BB} O_S S_I$) behavior (1757 mm) was significantly greater than the average stature associated with either of the one-step ($S_O C_{BB} S_I$) (1745 mm) or the even ($S_I O_C C_{BB} O_S S_I$) (1719 mm) stepping behaviors. Similarly, for the measure of Body Mass Index, the average BMI associated with the one-step behavior (23.1 kg/m$^2$) was significantly greater than the average BMI associated with either of the two-step (22.6 kg/m$^2$) or the even (21.9 kg/m$^2$) stepping behaviors.
The distribution of object mass (scaled by body mass) was not significantly different for any of the five stepping behaviors when compared within handedness conditions using the Tukey-Kramer HSD test ($p<0.05$). This result is counterintuitive to industry plant observations and general lifting guidelines which suggest that as object mass increases, a more conservative lifting strategy, particularly with respect to balance, should be selected. However, for the pooled data set, the average object mass (fraction of body mass) of the ipsilateral two-step ($S_C O_{1B} O_{C} S_I$) stepping behavior (0.0726*BM) was significantly greater than the average object mass associated with either of the one-step (0.0492*BM) or the two-step (0.0509*BM) stepping behaviors. Although not significantly different than any of the other behaviors, the average mass manipulated for the even stance behavior was (0.0655*BM).
3.5. Terminal Stance Configuration and Support Results

The instant at which the load changes state from being supported by a secondary surface to (or from) being supported by the human operator is commonly examined as part of an ergonomic task analysis. For the current study, this posture is defined as the ‘terminal posture.’ In a similar fashion, the ‘terminal stance’ is defined here as the relative configuration of the feet and the associated ground support during the terminal stance. Lifting studies traditionally report the ‘stance’ (usually the relative configuration only) an operator used during the lift or the frequency of occurrence of relative stances when summarizing multiple lifts (Authier et al., 1996; Kollmitzer et al., 2002; Plamondon et al., 2006). Stance is fairly easy to identify and provides potentially useful information regarding balance and lifting capability.

The nomenclature used here for stance and support are depicted earlier in Figure 3.7 and Figure 3.9. Split and even stances with a contralateral lead foot are graphically depicted in Figure 3.7.A and Figure 3.7.B, respectively. Full ground contact is defined as when both the toe and heel are in contact with the ground for both feet. Partial ground contact is defined by at least the toe or heel being in contact with the ground for each foot. Single foot ground contact is defined as only one foot (heel and/or toe) being in contact with the ground.

Split stance was most commonly observed (92.5% of transfer trials) with 13.8% of those split behaviors maintained with the ipsilateral limb as the lead foot and the remaining 86.2% maintained with the contralateral limb as the lead foot (Figure 3.15). Single limb ground contact terminal stance occurred during 67% of all transitions observed. Full and partial limb stance consisted of the remaining observed stances at 17.2% and 15.8% respectively. Ljungberg et al. (1989) and Authier et al. (1996) also reported a predominance of single limb support for self-selected lifting tasks.
3.6. Results for Task and Subject Variables on Foot Placements for the $S_{O_C}C_{bb}S_I$
(three step contralateral lead foot) Stepping Behavior

The most frequently observed stepping behavior group (from the automotive plant study, Chapter 2, and from the laboratory experiment presented here) is used to investigate the effects of turn angle, object weight, object position, and transfer hand on the positions and orientations of the foot placements during the behavior. Using the L-TRACS nomenclature described in Chapter 2, the one-step ($S_{O_C}C_{bb}S_I$) step behavior group can be described as follows: "The transition behavior begins with a step by the ipsilateral foot followed by a step with the contralateral foot at which time the load is manipulated while the lower extremities are in a split stance posture with the contralateral foot as the lead foot followed by a step with the ipsilateral foot along the new direction of progression." Three variables for each step ($X_i$, $Y_i$, $q_i$) totaling 9 variables are analyzed here. A graphical depiction of the parameterization for each step is reproduced from Figure 3.7A and shown here in Figure 3.16. As previously described, the parameterization of the third step of this behavior is defined in the departure coordinate system, and hence partially include the effects of turn angle.

The results are presented in the following subsections:

1. Independent effects and corresponding linear models of turn angle (by hand) for each of the nine step variables.
2. Interaction effects and ANOVA between turn angle, manipulation hand(s), and subject factors including stature and BMI for each of the nine step variables.

3. Effects of transfer hand on lateral placement of the lead foot.

4. Independent effects of object weight (by hand) and object height (by hand) for each of the nine step variables.

5. Interaction effects and ANOVA between turn angle, object weight, and object height, manipulation hand(s), stature, and BMI for each of the nine step variables.

Results for Step Variables as affected by Turn Angle and Transfer Hand, Independent Effects

The effect of turn angle on step positions and orientations included in the one-step \( (S_1\Omega_cC_{BB}S_i) \) stepping behavior are investigated. A subset of the pooled \( I_{A+B} \) trials in which the one-step \( (S_1\Omega_cC_{BB}S_i) \) stepping behavior was observed was used. The data analyzed included all transfers in the \( I_{A+B} \) data satisfying the following criteria: medium
weight, middle-to-middle shelf transfer, pickup manipulation, and transfer trials not associated with the departure distance sub-experiment (i.e. trials with the delivery distance code $a_i$ or $b_i$ as described in Table 3.2). Distributions of the transfer trials by subject number, observed turn angle, and transfer hand are presented in Figure 3.17.

A linear regression between turn angle and each stepping parameter is presented in Figure 3.18. A linear fit of turn angle was observed to be a significant ($p<0.01$) predictor with a $R^2$ adjusted value greater than 0.1 for the $X_2$, $X_3$, $q_1$, $q_2$, and $q_3$ stepping behavior parameters. Linear fits for each step parameter by turn angle were analyzed for the pooled data presented in Figure 3.17 and for the subsets of data grouped by the transfer hand condition. The same significant predictors and trends were found for each transfer hand data subset as for the pooled data (i.e. $R^2$ adjusted > 0.1 and $p<0.01$). The lone exception was observed for the $q_1$ stepping parameter for which the contralateral hand data set satisfied the criteria listed above while the ipsilateral and both handedness
data sets did not satisfy the criteria. However, the maximum difference between the linear fit lines between the contralateral and remaining three data sets was less than 5° over the observed range of turn angles. This difference was deemed negligible as the standard deviation of mean foot angles between male subjects (ages 20 to 60) as reported by Macellari et al. (1999) for straight line walking was 4.5°. As such, only the plots from the pooled data set are presented for clarity. Although similar trends were observed between the handedness conditions, the potential interactions between handedness and turn angle are investigated further when the models for each parameter are developed.

![Figure 3.18](image-url)

Figure 3.18. Bivariate plots of the nine stepping parameters of the one-step \((S_0,C_{100}S_1)\) stepping behavior (see Figure 3.7.A) by turn angle. Single regressor (turn angle) linear fit models and summary statistics are depicted for each stepping parameter. Grayed out plots indicate the linear fit was not significantly different \((p<0.01)\) from the mean parameter value and/or that the variance accounted for by the fit model \((R^2_{adjusted})\) was less than 0.1.

Turn angle was not observed to significantly affect the step parameters associated with fore-aft distance \((Y_2\) directly and \(Y_1\) and \(Y_3\) as measures of step length). However, turn angle was observed to have a significant effect on the lateral placement of the second
and third steps in addition to the orientation of each foot. The linear fit predicts that increasing the turn angle from 20° to 180° after the pickup results in on average a 50° decrease in foot orientation for the lead foot. The plot in Figure 3.18.C also suggests that for the defined 180° turn, the magnitude of the lead foot orientation (q₂) may be underestimated by the linear fit. The same trend observed between turn angle and q₂ also is observed for the orientation of the final step (q₃), although to a significantly smaller magnitude. This suggests that for larger turns, participants aggregate the necessary change in orientation between the q₂ orientation and the following two steps (i.e. q₃ and the following step). The linear fit suggests that the majority of the orientation change is accomplished during the 3rd step (i.e. when both hips are being externally rotated). However, the large range over which q₂ is observed also suggest that certain participants may favor a strategy in which larger internal hip rotation (by pre-orienting the lead foot) is the primary means for producing the change in heading.

The lateral foot placement of the lead foot (X₂) and the final step (X₃) were also significantly affected by changes in turn angle. The difference in the X₂ position being further ipsilateral with respect to the load for small turn angles than large ones is due partly to the fact that the pickup shelf obstructed the direct progression for small changes in direction. This same reasoning may also partly explain the larger step widths observed for the final step (X₃) for small turn angles as compared with larger changes in orientation in which the pickup shelf did not act as an obstruction.

ANOVA Results for Step Variables as Affected by Turn Angle, Transfer Hand, and Subject Characteristics

Multivariate regression models for each stepping parameter were generated to investigate any potential interactions between the regressors using the pooled data set. Two-way interactions were included for all control and anthropometric variables to examine the possibility that a particular step variable was scaled differently for different groups of task conditions in addition to any potential anthropometric effects. A step-wise procedure for model creation was applied using first, an automated procedure with p<0.01 to enter and p<0.05 to leave and second, an interactive procedure during which the contribution of included terms was evaluated in an effort to obtain a more parsimonious model. Terms were considered substantial and included in the final fit model if they (or an associated higher order term) were statistically significant with
p<0.01 *and* contributed to an increase in adjusted $R^2$ value of at least 0.02 over the corresponding model with the term excluded.

Two tables are presented for each dependent measure. The resulting regression models are tabulated and the coefficients for the significant terms, regression function intercept, adjusted $R^2$ value, and the root-mean-square-error are presented in the first table. The regression coefficients (for the linear terms only) are multiplied by the range of the continuous independent measures present in the data and presented in the second table. The range table allows for the direct interpretation of the effects of varying the control variables over the observed range in the data on the dependent measures. A similar interpretation of the multiplied ranges that make up the interaction terms would not yield an appropriate representation of the range for which the interaction affects the dependent measure. Instead, interaction plots are presented that show the effect of one interaction term over the observed limits (min and max) of the other interaction term on the dependent measure of interest are presented in the Appendix section 3.8.

Turn angle was included in all of the final regression models except the prediction of $Y_1$. Table 3.7 summarizes the included parameters and respective coefficients in each of the nine final fit models. Table 3.8 evaluates the included linear terms for each model over the range each independent variable was observed in the data. For example, the range in observed turn angle is 169°. Multiplying the coefficients from Table 3.7 by 169° indicates that the effect on the lateral position of the lead foot ($X_2$) of varying turn angle over this range is 0.133 (fraction of stature) while the effect on the fore-aft position of the same foot ($Y_2$) is 0.031 (fraction stature).
Table 3.7. Regression equations predicting step variables for the one-step (S_1O_2C_{BB}S_I) stepping behavior*. Step variables (X_i, Y_i) are reported in units of fraction of stature and q_i is reported in units of degrees. Refer to Figure 3.16 and the associated text for a description of the step variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X_1</th>
<th>Y_1</th>
<th>q_1</th>
<th>X_2</th>
<th>Y_2</th>
<th>q_2</th>
<th>X_3</th>
<th>Y_3</th>
<th>q_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.0993</td>
<td>-0.1126</td>
<td>-13.0</td>
<td>0.0712</td>
<td>-0.975</td>
<td>10.3</td>
<td>0.2134</td>
<td>0.2099</td>
<td>17.4</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-2.10e-4</td>
<td>--</td>
<td>0.0461</td>
<td>-7.88e-4</td>
<td>1.82e-4</td>
<td>-0.317</td>
<td>-1.31e-3</td>
<td>1.95e-4</td>
<td>-0.135</td>
</tr>
<tr>
<td>Transfer Hand (both</td>
<td>-1.24e-3</td>
<td>--</td>
<td>0.0461</td>
<td>-1.05e-3</td>
<td>2.21e-2</td>
<td>-0.278</td>
<td>1.24e-2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>contralateral ipsilateral</td>
<td>-1.15e-2</td>
<td>--</td>
<td>--</td>
<td>4.75e-2</td>
<td>-6.52e-3</td>
<td>-5.639</td>
<td>-1.97e-2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>8.07e-5</td>
<td>-0.0152</td>
</tr>
<tr>
<td>Body Mass Index (kg/m^2)</td>
<td>--</td>
<td>-8.56e-3</td>
<td>0.525</td>
<td>--</td>
<td>-4.37e-3</td>
<td>--</td>
<td>--</td>
<td>0.768</td>
<td></td>
</tr>
<tr>
<td>¶Turn Angle x Transfer Hand</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.120</td>
<td>4.99e-4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.123</td>
<td>-6.55e-4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R^2 (adjusted)</td>
<td>0.13</td>
<td>0.09</td>
<td>0.19</td>
<td>0.41</td>
<td>0.22</td>
<td>0.54</td>
<td>0.47</td>
<td>0.05</td>
<td>0.44</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.034</td>
<td>0.092</td>
<td>5.52</td>
<td>0.055</td>
<td>0.046</td>
<td>14.26</td>
<td>0.063</td>
<td>0.046</td>
<td>7.44</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† A -- indicates that the model coefficient was not significantly different from zero.
# Regressor not significant (p<0.01) alone, included because of a higher order effect or interaction
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 3.8. Range estimates using regression equations for the one-step (S_1O_2C_{BB}S_I) stepping behavior.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>X_1</th>
<th>Y_1</th>
<th>q_1</th>
<th>X_2</th>
<th>Y_2</th>
<th>q_2</th>
<th>X_3</th>
<th>Y_3</th>
<th>q_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn Angle (degrees)</td>
<td>168.8</td>
<td>-0.0354</td>
<td>--</td>
<td>7.78</td>
<td>-0.133</td>
<td>0.031</td>
<td>#</td>
<td>#</td>
<td>0.0329</td>
<td>-22.8</td>
</tr>
<tr>
<td>Transfer Hand</td>
<td></td>
<td></td>
<td>--</td>
<td></td>
<td>--</td>
<td>0.0939</td>
<td>0.038</td>
<td>#</td>
<td>#</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>375</td>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.030</td>
<td>-5.7</td>
<td></td>
</tr>
<tr>
<td>Body Mass Index (kg/m^2)</td>
<td>12.855</td>
<td></td>
<td>-0.11</td>
<td>6.75</td>
<td>--</td>
<td>-0.056</td>
<td>--</td>
<td>--</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>R^2 (adjusted)*</td>
<td></td>
<td></td>
<td></td>
<td>0.13</td>
<td>0.09</td>
<td>0.19</td>
<td>0.41</td>
<td>0.22</td>
<td>0.54</td>
<td>0.47</td>
</tr>
<tr>
<td>Root Mean Square Error*</td>
<td></td>
<td></td>
<td>0.034</td>
<td>0.092</td>
<td>5.52</td>
<td>0.055</td>
<td>0.046</td>
<td>14.26</td>
<td>0.063</td>
<td>0.046</td>
</tr>
</tbody>
</table>

* Values repeated from Table 3.7.
† A zero indicates that the model coefficient was not significantly different from zero.
# Regressor involved in higher order or interaction effect, refer to interaction plots below.
‡ Ranges for nominal variables are defined as the largest possible range between the regressor coefficients.

The range estimates, R^2 values, and root-mean-square-error (RMSE) values in Table 3.8 indicate the relative importance of the anthropometric and test variables in determining foot placements and orientations for the one-step (S_1O_2C_{BB}S_I) stepping behavior. The step width (X_1) and length (Y_1), scaled by stature, of the first step measured...
with respect to the second is poorly predicted by the available variables. However, the RMSE for X, is fairly small, indicating that the overall range of variability in the data is also small. The RMSE value for Y is approximately 2.7 times larger than that for X, indicating that not only is the step length prior to the terminal stance poorly predicted by the potential predictors (R² value of 0.09), the range of step lengths in the data is fairly large (coefficient of variation of 31%).

The orientation of the first step (q₁) relative to the approach direction is also poorly predicted overall, with a R² of 0.19. However, the RMSE is small compared with the variability between subjects for foot angle measures published for straight line walking. Turn angle and Body Mass Index are both fairly equivalent predictors with larger first step orientations associated with an increase in turn angle and individuals with higher BMIs.

The lateral placement of the lead foot (X₂), the orientation of the lead foot (q₂), the step width associated with the final step (X₃), and the orientation of the final step (q₃) are all predicted moderately well by the regressions. The regression equations of the q₂ and X₃ variables involve interactions between turn angle and transfer hand and cannot be directly interpreted with the range estimates in Table 3.8. Further interpretations of those interactions are investigated later with the interaction plots for each variable, and are further examined in the Appendix section. For both X₂ and q₃, turn angle is the most important predictor. In both cases, larger turn angles are associated with a decrease in the respective step variable (i.e., the lead foot placement is further contralateral with respect to the turn direction and the final step angle is oriented more toward the contralateral side of the departure vector). The transfer hand(s) is also an important determinant of the lateral position of the lead foot (X₂). Across all the observed turn angle trials, the mean X₂ value measured for the two-handed lifting trials is -0.0125*stature. The difference between the mean X₂ two-handed trials and the contralateral and ipsilateral handed lifting trials is 0.0465*stature and -0.0356*stature, respectively. For example, a one handed lift followed by a turn toward the right, the contralateral (left) lead foot is farthest to the left when the lift is performed with the right arm, and farthest to the right when the lift is performed with the left arm. The significant trend in lateral foot placement suggests that...
for one handed lifting tasks, participants may prefer lifting postures in which the shoulder or upper arm is aligned with the load as opposed to the support foot or pelvis.

The fore-aft position of the lead foot ($Y_2$) and the step length of the final step ($Y_3$) are not well predicted by the test and anthropometric variables, with $R^2$ values of 0.22 and 0.05, respectively. However, the RMSE values indicate that the ranges of both parameters in the data are fairly small. The most powerful predictor of fore-aft distance between the lead foot and the load is BMI, with larger BMI individuals standing slightly farther away from the load (on average $0.056\times$stature) than individuals with smaller BMIs. Stature and turn angle each have small effects on the final step length, corresponding to about 6 cm for a 180 cm tall individual for both the 375 cm and 168.8° stature and turn angle ranges, respectively.

Results for the Transfer Hand Effects on Lateral Lead Foot Placement ($X_2$)

The effect of transfer hand on the lateral placement of the lead foot is now investigated. A subset of the trials used for the analysis in the previous section was selected. Trials with the same task conditions that were performed by the same subject with the only difference being the hand(s) used to perform the transfer were grouped. Ninety trials were selected to form 30 matched trials. Paired t-tests were calculated between the each three transfer hand conditions with the paired differences summarized in Table 3.9.

Table 3.9. Summary of paired t-tests between selected ipsilateral, contralateral, and both handed transfers.

<table>
<thead>
<tr>
<th>Paired hand(s)</th>
<th>$X_a$ mean, first in pair (fraction of stature)</th>
<th>$X_b$ mean, second in pair (fraction of stature)</th>
<th>$X_a - X_b$ Mean Difference (fraction of stature)</th>
<th>Standard Error (fraction of stature)</th>
<th>t-Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ipsilateral - Contralateral</td>
<td>-0.0437</td>
<td>0.04377</td>
<td>-0.0875</td>
<td>0.0072</td>
<td>-12.1</td>
</tr>
<tr>
<td>Both - Contralateral</td>
<td>0.0165</td>
<td>0.04377</td>
<td>-0.0273</td>
<td>0.00624</td>
<td>-4.37</td>
</tr>
<tr>
<td>Both - Ipsilateral</td>
<td>0.0165</td>
<td>-0.0437</td>
<td>0.0602</td>
<td>0.00756</td>
<td>7.96</td>
</tr>
</tbody>
</table>

*all pairings were significant $p<0.01$

The lateral placement of the lead foot for the most commonly observed behavior, one-step ($S_{O_{1}}C_{BB}S_0$), was significantly different ($p<0.01$) for each transfer hand(s) used. For a 175 cm tall person performing a right turn following the transfer, the lead foot lateral position (with 0 being defined as directly in line with the center of the transfer object and the positive values being to the right of that center line) for a right, both, and
left handed transfer are -7.6 cm, 2.9 cm, and 7.7, respectively. The standard error measures of the calculated difference between each possible pairing were comparable (approximately 0.007*stature). Taking the largest standard error of the three pairings (both-ipsilateral), the associated error in the difference between lateral lead foot placements when using the different transfer hands for the 175 cm tall person is 1.225 cm.

Results for Step Variables as Affected by Object Weight and Height, Independent Effects

The effects of object weight and pickup height, in addition to potential interactions involving turn angle, on the nine stepping parameters of the one-step \( (S_iO_cC_{bb}S_i) \) stepping behavior are investigated here. A subset of the pooled \( I_{A+B} \) trials in which the one-step \( (S_iO_cC_{bb}S_i) \) stepping behavior was observed was used. The data analyzed included all transfers in which one-step \( (S_iO_cC_{bb}S_i) \) stepping behavior was observed in addition to satisfying the following trial criteria: all hand conditions, all object types, all shelf heights, pickup transfers only, defined turn angles of 90°, 135°, 180°, and departure distance trials with the delivery distance code of ‘5p4’ as listed in Table 3.2. Distributions of the transfer trials grouped by subject, shelf height as a nominal variable, and transfer hand separated by object type and defined turn angle are presented in Figure 3.19.
Figure 3.19. Distributions of transfer trials used to investigate the effects of object mass and transfer height on the foot positions and orientations for the one-step (SIOCBBSS) stepping behavior. Transfer trials are grouped by A) Subject Number, B) Shelf Height, C) Turn Angle by Lifting Hand, and D) Object Type (one and two handed weights are defined independently).

The distribution of trials observed in the pooled data set used for analysis in this section have a disproportionate number of trials in which the load was lifted from the middle shelf height. Additionally, the method for selecting the trials included in the data set used here nearly guarantees each trial factor will not be observed over all possible conditions. The varying number of trials for each subject must also be acknowledged as a potential source of bias in the results presented here. As such, the majority of comparisons within this section are made using the Tukey-Kramer HSD test (Tukey, 1953; and Kramer, 1956), which compares the differences between group means. For sample sizes that are the same, the Tukey-Kramer HSD test is an exact alpha-level test. For group samples sizes that are different, the Tukey-Kramer HSD test is conservative (Hayter, 1984) when identifying significantly different means. A significance level of p<0.05 is used for all the nominal comparisons in this section.
Shelf Height Results

Bivariate comparisons for the nine stepping parameters of the one-step (SiOcCbbSi) stepping behavior were analyzed by shelf height (nominally defined as low, middle, and high). The nine bivariate plots were analyzed for the contralateral hand trials only, the ipsilateral hand trials only, two-handed trials only, and the pooled data set to identify any potential differing trends and/or interactions involving handedness. Handedness was observed to significantly change the trend and significance for some stepping parameters. Particularly, the position of the lead foot (X2, Y2) with respect to the load was observed to be significantly different between shelf height groups for the one-handed data subsets while no significant difference was observed for the two-handed trials. As such, the comparisons between shelf heights are presented independently for the contralateral, ipsilateral, and both handed conditions (Figure 3.20). Comparison between the different shelf height conditions for the X1 and Y1 stepping parameters are excluded in Figure 3.20 because no significant difference in mean values was observed between any of the shelf pairings. For all other stepping parameters, at least one shelf pairing was significantly different for one of the handedness conditions. Grayed out plots in Figure 3.20 signify no difference between any of the shelf pairings for that stepping parameter and handedness combination was observed to be significant.
Figure 3.20. Bivariate plots of the nine stepping parameters of the one-step (S\textsubscript{10}, C\textsubscript{10}, S\textsubscript{1}) stepping behavior (see Figure 3.7.A) by manipulation shelf, for each lifting hand(s). Mean responses for each shelf height (low, middle, and high) were all compared using the Tukey-Kramer HSD test with a significance of p<0.05. The diamonds represent the 95% confidence interval of the sample mean for that set of data. The circles to the right of each plot depict a graphical method for identifying significance between two sample means. Circles for means that are significantly different do not intersect or intersect slightly. Grayed out plots indicate no shelf height pair was significantly different for that hand(s) and step parameter combination.
Pickup height affected both foot positions and orientations. The step length and width (measured with respect to the lead foot of the behavior) were not significantly affected by shelf height. However, for the low shelf conditions (0.15*participant stature above the floor), the orientation of the first step was significantly more outwardly rotated than for the other shelf conditions for all handedness conditions. The largest significant difference in orientation between the low shelf condition and the middle or high shelf condition for the contralateral, ipsilateral, and both handed lifts are 6.8°, 4.3°, and 9.7°, respectively. For the lead foot position \((X_2, Y_2)\), the one handed lifts are observed to follow the same trend in which an increase in shelf height is associated with a shift in lateral foot placement toward the ipsilateral direction. The same increase in shelf height is also associated with an increase in distance between the lead foot and the load in the fore-aft direction for the one-handed trials. Shelf height only significantly affected the lead foot orientation for the ipsilateral handed lifts. A fairly linear trend of the foot orientation means for the three shelf heights was observed in which as shelf height decreased, the magnitude of inward rotation of the lead foot increased. The final step width \((X_3)\) and length \((Y_3)\) for all the handedness conditions were significantly affected for at least one of the shelf height pairings. Interestingly, the trend between the shelf height groups was similar for the contralateral and both handedness conditions, and suggests a nonlinear relationship with the \(X_3\) step parameter.

**Object Mass Results**

The effect of the mass of the object on the nine stepping parameters was investigated in a similar fashion to the effect of shelf height. Object mass was nominally grouped into light, medium, and heavy categories. It should be recalled that the mass ranges for the one and two-handed objects were different. In addition to the analysis of nominal object weights, linear models, similar to those used to investigate the effects of turn angle, were fit after normalizing object mass with respect to participant body mass. The nominal comparisons were made using the Tukey-Kramer HSD test with a significance of \(p<0.05\). The linear fit models were retained if they were significant \((p<0.01)\) and the overall fit resulted in an adjusted \(R^2 > 0.1\). Within the separate contralateral, ipsilateral, and two-handed data subsets, only one stepping parameter was significantly affected by the change in object mass. Figure 3.21 depicts the significant
nominal comparisons between object mass for the $Y_2$ stepping parameter for the contralateral and both handed conditions. The only linear fit of object mass (scaled by body mass) to any of the stepping parameters that was interpreted as considerable was the $Y_2$ parameter for the contralateral handed lifts in which heavier loads resulted in the lead foot being positioned closer to the load.

A linear trend between the nominal comparisons for the contralateral-handed trials of the $Y_2$ stepping parameter is observed. The same trend is reflected in the linear fit using object mass (scaled by body mass). A similar linear trend, although not

Figure 3.21. Bivariate plots of the $Y_2$ stepping parameter of the one-step ($S_{O,C_{BB},S}$) stepping behavior (see Figure 3.7.A) by object mass grouped by lifting hand. Single regressor (object mass) linear fit models and summary statistics are depicted for each stepping parameter. Mean responses for each object type (light, medium, and heavy) were all compared using the Tukey-Kramer HSD test with a significance of $p<0.05$. Grayed out plots indicate the linear fit was not significantly different ($p<0.01$ for linear fit) from the observed mean value and/or that the variance accounted for by the fit model ($R^2$ adjusted) was less than 0.1.

A linear trend between the nominal comparisons for the contralateral-handed trials of the $Y_2$ stepping parameter is observed. The same trend is reflected in the linear fit using object mass (scaled by body mass). A similar linear trend, although not
significant in either the linear fit or nominal comparisons, is observed for the ipsilateral
dhanded trials as well. For the two-handed data set, the same trend is observed between
the significant medium and heavy load comparison, although the mean value of $Y_2$ for the
light load suggests a potential nonlinear effect. A second-order polynomial fit to the two-
handed $Y_2$ data by object mass (scaled by body weight) improved the fit, but the adjusted
$R^2$ value did not exceed the criterion value of 0.1.

ANOVA Results for Step Variables as Affected by Task and Subject Characteristics

Regression analyses were performed using the same step-wise procedure used to
investigate the potential interactions involved with turn angle. The automated procedure
was applied using $p<0.01$ to enter and $p<0.05$ to leave. The Body Mass Index (BMI),
defined as the body mass of the subject divided by the square of the stature ($\text{kg}/\text{m}^2$), is
used in place of body mass alone to include a representation of body mass that is less
correlated with stature. In the pooled $I_{A+B}$ data, the correlation between BMI and stature
is 0.097. Distance measures (including the stepping parameters and manipulation height)
are all normalized by subject stature. Object mass is normalized by subject body mass to
facilitate direct comparisons across subjects (Pierrynowski, 2001).

Although the nominal comparisons and linear fits presented in Figure 3.20 and
Figure 3.21 suggest that the majority of trends for each stepping variable are consistent
across the handedness conditions, some trends differ across handedness conditions,
particularly for $X_3$ and $Y_2$. These results suggest that potential interactions between
handedness, object weight, and shelf height may be significant. However, the
interactions explored here by any one mode are constrained to second-order effects for
clarity and interpretability. Consequently, independent regression models for each
handedness data set were computed and compared to investigate any potential three-way
interactions involving lifting hand. All terms and each model are statistically significant
with $p<0.05$. Potential regressors included stature, BMI, pickup height scaled to stature
(continuous), object mass scaled to body mass (continuous), turn angle (a subset of those
investigated in the previous section), the two-way interactions between those regressors
previously listed, and the 2$^{nd}$ order terms for pickup height and object mass. Nonlinear
effects that entered the final regression models were observed for the manipulation
height, and included in the fit models for the $q_1$, $Y_2$, and $X_3$ stepping parameters. Two
interactions involving turn angle and object mass, and pickup height and BMI were included for the $X_3$ and $q_3$ regression models, respectively, for the two handed lifts (Figure 3.24 in Appendix 3.8). The interaction between turn angle and pickup height was also included for the $q_1$ and $Y_3$ fit models for the contralateral handed lifts (Figure 3.24). No interactions were included for any of the fit models involving the ipsilateral handed lifts.
Table 3.10. Regression equations predicting the step variables for the one-step (SI, CC) stepping behavior in which the contralateral lifting hand was used*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X₁</th>
<th>Y₁</th>
<th>q₁</th>
<th>X₂</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.100</td>
<td>-0.303</td>
<td>-10.75</td>
<td>0.212</td>
<td>-0.053</td>
<td>74.14</td>
<td>0.021</td>
<td>0.115</td>
<td>16.64</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-6.82e-4</td>
<td>--†</td>
<td>0.109</td>
<td>-1.67e-3</td>
<td>--</td>
<td>-0.763</td>
<td>-3.77e-4</td>
<td>-2.26e-4</td>
<td>-0.111</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.694</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>-11.21</td>
<td>0.060</td>
<td>-0.080</td>
<td>-19.17</td>
<td>-0.034</td>
<td>-0.076</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.55e-4</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>2.34e-3</td>
<td>--</td>
<td>0.359</td>
<td>--</td>
<td>-4.62e-3</td>
<td>--</td>
<td>4.25e-3</td>
<td>2.52e-3</td>
<td>0.840</td>
</tr>
<tr>
<td>Manipulation Height² ‡</td>
<td>--</td>
<td>--</td>
<td>27.56</td>
<td>--</td>
<td>-0.127</td>
<td>--</td>
<td>0.173</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height x Turn Angle ‡</td>
<td>--</td>
<td>--</td>
<td>-0.166</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-9.89e-4</td>
</tr>
<tr>
<td>R² (adjusted) *</td>
<td>0.35</td>
<td>0.00</td>
<td>0.39</td>
<td>0.69</td>
<td>0.43</td>
<td>0.68</td>
<td>0.17</td>
<td>0.40</td>
<td>0.21</td>
</tr>
<tr>
<td>Root Mean Square Error *</td>
<td>0.03</td>
<td>0.10</td>
<td>5.84</td>
<td>0.03</td>
<td>15.6</td>
<td>0.05</td>
<td>0.03</td>
<td>7.95</td>
<td>--</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 3.11. Range estimates using regression equations for the one-step (SI, CC) stepping behavior in which the contralateral lifting hand was used.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>X₁</th>
<th>Y₁</th>
<th>q₁</th>
<th>X₂</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn Angle (deg.)</td>
<td>83.8</td>
<td>-0.057</td>
<td>--†</td>
<td>--</td>
<td>-0.140</td>
<td>--</td>
<td>-63.9</td>
<td>-0.032</td>
<td>--</td>
<td>-9.3</td>
</tr>
<tr>
<td>Obj. Mass (fraction of body mass)</td>
<td>0.0846</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.059</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>MH (fraction of stature)</td>
<td>0.783</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.047</td>
<td>0.064</td>
<td>-15.0</td>
<td>0.041</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>375</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.058</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>12.9</td>
<td>0.030</td>
<td>--</td>
<td>4.6</td>
<td>--</td>
<td>-0.059</td>
<td>--</td>
<td>0.055</td>
<td>0.032</td>
<td>10.8</td>
</tr>
<tr>
<td>R² (adj.) *</td>
<td>--</td>
<td>0.35</td>
<td>0.00</td>
<td>0.39</td>
<td>0.69</td>
<td>0.43</td>
<td>0.68</td>
<td>0.17</td>
<td>0.40</td>
<td>0.21</td>
</tr>
<tr>
<td>RMSE*</td>
<td>--</td>
<td>0.03</td>
<td>0.10</td>
<td>5.84</td>
<td>0.03</td>
<td>0.04</td>
<td>15.6</td>
<td>0.05</td>
<td>0.03</td>
<td>7.95</td>
</tr>
</tbody>
</table>

* Values repeated from Table 3.10.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Regressor involved in second order effect. Range estimate is the combined effects for the linear and second order terms over the ranges observed in the data.
Table 3.12. Regression equations predicting the step variables for the one-step (S_{IO_{C_{BB}}S_{I}}) stepping behavior in which both lifting hands were used*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X₁</th>
<th>Y₁</th>
<th>q₁</th>
<th>X₂</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.224</td>
<td>-0.115</td>
<td>-5.89</td>
<td>0.290</td>
<td>-0.153</td>
<td>57.36</td>
<td>0.130</td>
<td>0.106</td>
<td>34.888</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-9.31e-4</td>
<td>- propagating value</td>
<td>0.121</td>
<td>-2.25e-3</td>
<td>6.86e-4</td>
<td>-0.629</td>
<td>-3.41e-4</td>
<td>--</td>
<td>-0.127</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>-0.032</td>
<td>--</td>
<td>-7.86</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.060</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.68e-4</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>--</td>
<td>-8.31e-3</td>
<td>--</td>
<td>--</td>
<td>-0.004</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.669</td>
</tr>
<tr>
<td>Manipulation Height² ‡</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.281</td>
</tr>
<tr>
<td>Manipulation Height x BMI ‡</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2.177</td>
</tr>
<tr>
<td>Turn Angle x Object Mass_%BM ‡</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-6.01e-3</td>
</tr>
<tr>
<td>R² (adjusted)</td>
<td>0.41</td>
<td>0.07</td>
<td>0.29</td>
<td>0.83</td>
<td>0.22</td>
<td>0.65</td>
<td>0.18</td>
<td>0.29</td>
<td>0.32</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.03</td>
<td>0.10</td>
<td>5.81</td>
<td>0.03</td>
<td>0.04</td>
<td>12.92</td>
<td>0.06</td>
<td>0.03</td>
<td>6.67</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 3.13. Range estimates using regression equations for the one-step (S_{IO_{C_{BB}}S_{I}}) stepping behavior in which both lifting hands were used.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>X₁</th>
<th>Y₁</th>
<th>q₁</th>
<th>X₂</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn Angle (deg)</td>
<td>80.5</td>
<td>-0.075</td>
<td>--</td>
<td>9.8</td>
<td>-0.181</td>
<td>0.055</td>
<td>-50.7</td>
<td>--</td>
<td>--</td>
<td>-10.2</td>
</tr>
<tr>
<td>Obj. Mass (fraction of body mass)</td>
<td>0.2589</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>MH (fraction of stature)</td>
<td>0.783</td>
<td>-0.025</td>
<td>--</td>
<td>-6.2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.056</td>
<td>-0.041</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>375</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.063</td>
<td>-8.5</td>
<td></td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>12.9</td>
<td>--</td>
<td>-0.107</td>
<td>--</td>
<td>--</td>
<td>-0.047</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R² (adj) *</td>
<td>--</td>
<td>0.41</td>
<td>0.07</td>
<td>0.29</td>
<td>0.83</td>
<td>0.22</td>
<td>0.65</td>
<td>0.18</td>
<td>0.29</td>
<td>0.32</td>
</tr>
<tr>
<td>RMSE*</td>
<td>--</td>
<td>0.03</td>
<td>0.10</td>
<td>5.81</td>
<td>0.03</td>
<td>0.04</td>
<td>12.92</td>
<td>0.06</td>
<td>0.03</td>
<td>6.67</td>
</tr>
</tbody>
</table>

* Values repeated from Table 3.12. † -- indicates that the model coefficient was not significantly different from zero. ‡ Regressor involved in second order effect. Combined order effects for the linear and second order terms over the ranges observed in the data are presented.
Table 3.14. Regression equations predicting the step variables for the one-step ($S_I$O$_C$C$_{BB}$S$_I$) stepping behavior in which the ipsilateral lifting hand was used*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.109</td>
<td>-0.101</td>
<td>-20.28</td>
<td>0.159</td>
<td>-0.337</td>
<td>32.03</td>
<td>0.180</td>
<td>0.150</td>
<td>8.938</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-5.06e-4</td>
<td>--</td>
<td>0.102</td>
<td>-1.64e-3</td>
<td>5.88e-4</td>
<td>-0.385</td>
<td>-1.39e-3</td>
<td>--</td>
<td>-0.130</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.396</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>-10.09</td>
<td>--</td>
<td>-0.079</td>
<td>--</td>
<td>-0.089</td>
<td>-0.060</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.42e-4</td>
<td>--</td>
<td>--</td>
<td>1.46e-4</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>2.46e-3</td>
<td>-8.84e-3</td>
<td>0.634</td>
<td>--</td>
<td>-6.56e-3</td>
<td>--</td>
<td>3.95e-3</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

| Manipulation Height*$^2$ ‡ | -- | -- | 28.66 | -- | -- | -- | -- | -- | -- |

| $R^2$ (adjusted) | 0.28 | 0.09 | 0.50 | 0.58 | 0.52 | 0.38 | 0.30 | 0.36 | 0.10 |
| Root Mean Square Error | 0.02 | 0.09 | 4.82 | 0.03 | 0.04 | 10.24 | 0.05 | 0.03 | 8.11 |

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 3.15. Range estimates using regression equations for the one-step ($S_I$O$_C$C$_{BB}$S$_I$) stepping behavior in which the ipsilateral lifting hand was used.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn Angle (degrees)</td>
<td>78.4</td>
<td>-0.040</td>
<td>--</td>
<td>8.0</td>
<td>-0.128</td>
<td>0.046</td>
<td>-30.1</td>
<td>-0.109</td>
<td>--</td>
<td>-10.2</td>
</tr>
<tr>
<td>Obj. Mass (fraction of body mass)</td>
<td>0.0846</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.034</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>BMI (fraction of stature)</td>
<td>0.783</td>
<td>--</td>
<td>--</td>
<td>10.1</td>
<td>--</td>
<td>-0.062</td>
<td>--</td>
<td>-0.069</td>
<td>-0.047</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>375</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.053</td>
<td>--</td>
<td>--</td>
<td>0.055</td>
<td>--</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>12.9</td>
<td>0.032</td>
<td>-0.114</td>
<td>8.1</td>
<td>--</td>
<td>-0.084</td>
<td>--</td>
<td>0.051</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

| $R^2$ (adj.) *                        | --     | 0.28  | 0.09  | 0.50  | 0.58  | 0.52  | 0.38  | 0.30  | 0.36  | 0.10  |
| RMSE*                                 | --     | 0.02  | 0.09  | 4.82  | 0.03  | 0.04  | 10.24 | 0.05  | 0.03  | 8.11  |

* Values repeated from Table 3.14.
† -- indicates that the model coefficient was not significantly different from zero.
# Regressor involved in interaction effect, refer to interaction plots below.
‡ Regressor involved in second order effect. Combined order effects for the linear and second order terms over the ranges observed in the data are presented.
The range estimates, $R^2$ values, and root-mean-square-error (RMSE) values in Table 3.11, Table 3.13, and Table 3.15 indicate the relative importance of the anthropometric and test variables in determining foot placements and orientations for the one-step ($S_{OC}C_{BB}S_{I}$) stepping behavior. For the lifts with the contralateral hand, $X_i$ and $q_i$ are predicted moderately well by the fit models. The most powerful predictor of $X_i$ is turn angle, with larger turn angles being associated with smaller step widths between the first and second step. BMI also significantly contributes to the lateral placement of the first step with respect to the second with individuals with larger BMIs tending to have wider step widths. The final $q_i$ fit model includes an interaction effect between turn angle and pickup height and is investigated later in the Appendix (Figure 3.24). The fore-aft placement of the first step, $Y_1$, is poorly associated with the anthropometric and test variables and no independent variable was included in the final model. Additionally, the relatively large RMSE value suggests that the variation observed in the data also is large for the step length prior to when the load is lifted.

The $X_2$ and $q_2$ variables for the contralateral-handed lifts are well predicted (adjusted $R^2$ of 0.69 and 0.68, respectively) by the test variables with turn angle being the most powerful predictor in both cases. Pickup height also contributes to a lesser degree as a regressor for both step variables, with higher lifting heights associated with more inward rotation of the lead foot in addition to steps being placed further contra-laterally to the load. However, the relatively large RMSE in addition to the high $R^2$ value associated with the $q_2$ fit model suggests that $q_2$ varies over a large range of angles and that the remaining variation after the fit is applied is still quite substantial. The fore-aft distance between the lead foot and load is predicted moderately well by the test and anthropometric variables. The included regressors of object mass (scaled to body mass), pickup height (scaled to stature), and BMI, all vary $Y_2$ over approximately the same amount with respect to the observed ranges of the variables in the data.

The $X_3$ and $q_3$ stepping parameters are poorly predicted by the test and anthropometric variables. However the relatively low RMSE value associated with $X_3$ suggests that the variation in of that step parameter in the data also is relatively small. The final step length $Y_3$ is predicted moderately well by the regression model. However the $Y_3$ fit model includes an interaction between turn angle and pickup height, which is
investigated later in Appendix 3.8. Stature and BMI are included as variables in the Y_3 regressions with taller individuals tending to have larger step lengths (after scaling for stature). A similar trend between BMI and Y_3 is also observed, with larger BMI associated with larger step lengths.

The regression models developed for the ipsilateral pickups share similar trends with the associated contralateral-handed regressions. Of particular interest are the similar RMSE values between the handedness conditions for each stepping parameter model. Additionally, a consistent set of test and anthropometric variables are included as significant for the stepping parameter fit models between the one handed conditions. For example, the X_1 fit model for both the ipsilateral and contralateral handedness conditions include turn angle as the most powerful predictor and BMI as also significantly contributing. The fit models for the ipsilateral handed tasks did not include any interaction effects. However, a second-order effect of pickup height was included as significant for the q_1 parameter, and was included, similar to the q_1 fit model presented for the contralateral-handed lifts.

The fit models for the Y_1, X_2, q_2, and Y_3, stepping parameters developed with the two handed lifting data are consistent with the respective fit models developed with the ipsilateral lifting data. The most powerful predictors for each fit model were the same between the one and two-handed regressions. The fit models for Y_1 and Y_3 were observed to have lower adjusted R^2 values, and slightly higher RMSE values for the two-handed trials than for the ipsilateral lifts. For these stepping parameters, this suggests that for the two-handed trials, the potential regressors are not as well associated with the stepping parameters as for the ipsilateral handed lifts. However, the X_2 and q_2 stepping parameter fit models exhibited the opposite trend, with higher R^2 values and lower RMSE for the two-handed lifting trials. The step width between the first and second step (X_1), the orientation of the first step (q_1), and the orientation of the final step (q_3) were all predicted moderately well by the regressions. The most powerful predictor for the X_1 and q_1 fit models is turn angle. Pickup height is also related to both the stepping parameters with higher heights being associated with smaller values of X_1 and q_1. Y_2 and X_3 were poorly predicted by the anthropometric and test variables. However, the small RMSE for the Y_2 fit model suggests that the variation of the fore-aft distance of the lead foot as
observed in the data is also small. The RMSE for the $X_3$ fit model is relatively large. An interaction between turn angle and object mass did enter the model and is investigated with the associated interaction plot in Appendix 3.8 (Figure 3.24).

3.7. **Summary and Discussion**

A laboratory study was conducted to determine the potential effects of turn angle, manipulation location, handedness, and object mass on foot placements. Analysis focused on the most frequently observed stepping behaviors. The principal observations that follow support the hypotheses derived from the field study and literature:

- Transfer type, lifting hand, shelf height, and turn angle each have significant effects on step behavior selection.
- Over the conditions studied, split stance is predominantly selected as the terminal stance, accounting for 92.5% of the total transfers observed.
- Two-thirds of object pickups and deliveries were accomplished with only one foot in contact with the ground.
- Turn angle and handedness (left, right, or both) are the primary determinants of the lateral placement of the lead foot for the most frequently observed (38.7% of transfers performed in the laboratory study) stepping behavior ($S_{O_cC_{BB}S_1}$, three step contralateral lead foot). Manipulation height (fraction of stature) also has a significant effect for the contralateral-handed transfers.
- The lateral placement of the lead foot was symmetric about the approach vector for the ipsilateral and contralateral handed transfers. The most contralateral foot placements were associated with the ipsilateral handed transfers.
- The fore-aft placement of the lead foot of the same stepping behavior is influenced by object mass (scaled by body mass) and BMI (adjusted $R^2$ of 0.25 for the contralateral handed transfers) for the one handed transfers. Second-order effects of manipulation height also were significant for the contralateral-handed transfers and resulted in an adjusted $R^2$ of 0.42 when included in the fit model. Turn angle and BMI were observed to be significant for the two handed transfers (adjusted $R^2$ of 0.22).
• Turn angle strongly influences the orientation of the terminal stance lead foot ($R^2$ of 0.48 across all handedness conditions for middle shelf and medium mass transfers). When first order interactions between transfer hand(s) and turn angle were included, the resulting adjusted $R^2$ was 0.54. Manipulation height also was observed to be significant for contralateral-handed transfers. When included with turn angle, the resulting model adjusted $R^2$ was 0.65.

Although similar stepping behaviors did exist in both the automotive and laboratory behavior distributions, the order of the most frequently occurring behavior groups between the two studies is not directly consistent. One possible explanation may be attributed to the fact that although the laboratory experiment was designed to cover the breadth of tasks observed throughout the assembly plant, the frequency of tasks was not matched. Another possible explanation may be due to the different methods used in each study for identifying the behaviors. In the automotive study, independent raters watching video recordings of each transfer identified the behaviors visually. In the laboratory study, a computer algorithm using foot position and timing data with respect to the estimated direction of progression automatically identified each step and behavior (see Chapter 2 for a description of the algorithm). Specifically, the discrepancy between the second most frequent behavior observed in the laboratory study (two-step, $S_I O_C C_{BB} O_S S_C$ step behavior) and that same behavior in the automotive study may be due to the inability of the raters in the latter study to distinguish the foot orientation with respect to the direction of progression from the video recording. If that were the case, the two-step ($S_I O_C C_{BB} O_S S_C$) step behavior may have been misidentified and labeled as the similar one-step ($S_I O_C C_{BB} S_I$) behavior, which would help explain the difference in prevalence of those behaviors between the two studies.

The cross over ($S_C O_I I_{BB} S_C$) stepping behavior was observed during manipulations involving turns with angles significantly lower than the previously mentioned behaviors. In fact, one-step ($S_I O_C C_{BB} S_I$) was not observed to be used with any turn angle greater than 145°. One potential reason for the association between this stepping behavior and smaller turn angles may be attributed to balance maintenance requirements. For example, for a turn toward the right-handed direction after manipulating a load, the feet are in split
stance with the right foot in front. Ignoring the potential for a collision between the subsequent left footstep and the shelf tower, the stepping behavior can be considered risky because of the left foot crossing over the right foot to complete the turn. At the instant the left foot contacts the ground, the extremities may be crossed, increasing the risk of tripping during the next step. For larger turn angles, this tripping condition becomes more pronounced and potentially increasingly hazardous.

The turn angles associated with the two-step ($S_iO_C C_{bb} O_S S_C$) stepping behavior did range from 54° to 254°, although 95% of the associated turn angles were observed within the range of 181.5° and 101.5°. One potential explanation for the unexpected use of this behavior when negotiating relatively small turn angles may be associated with the scheme used for behavior grouping and the obstacle created by the shelf tower itself. For example, the $O_I$ step defined by the behavior group for the relatively small turn angles may be better classified by the non-grouped behavior nomenclature as a ‘Move’ ($M_i$) step in which the orientation of the step may have been in line with the new direction of progression, but the step length may have been negligible. However, the $O_I$ nomenclature is used for all the $M_i$, $O_i$, and $P_i$ (pivot) steps when the specific behaviors were grouped into a single category (see Chapter 2 for how the nomenclature was defined). For the trials associated with small turn angles, the move step was used to navigate around the shelf tower obstacle following the manipulation. For the trials associated with the large turn angles, the $O_I$ orientation step was primarily observed in conjunction with a significant step length. However, the orientation of that step did not fall within the 30° threshold range of the final departure vector. In this case, the $O_I$ step might be better interpreted as a step taken along a curved path.

The variance in the behavior selection process is not fully explained by the anthropometric measures of stature and BMI alone. Perhaps additional and/or different participant anthropometrics may be better related to the step behavior selection process, particularly range of motion of the lower extremities. However that type of investigatory analysis is beyond the scope of the research presented here. Provided that each subject was presented with relatively the same trial task conditions, Figure 3.14 suggests that certain behaviors were preferred over others and that preference was potentially different for each participant. However, it is clear the one-step ($S_iO_C C_{bb} S_i$) and the two-step
(S_{i}O_{c}C_{bb}O_{i}S_{c}) stepping behaviors were preferred over the other behaviors for all participants. For example, across each of the participants, the sum of those two stepping behaviors accounted for over seventy percent of the selected behaviors presented here.

The effects analyses between subject and task factors on the step variables of the most commonly observed behavior demonstrated that turn angle, object weight, lifting height, and lifting hand all have statistically significant effects. Lifting hand and turn angle were observed to primarily affect the lateral placements (i.e. step width) and orientation of the feet. However, the fore-aft foot parameters were also affected to a lesser degree. Considered independently, object weight was observed to significantly affect only the fore-aft position of the lead foot when manipulating the load. Manipulation height was observed to affect primarily the fore-aft foot placement step parameters although it also significantly affected lateral and orientation parameters as well. Significant interactions were observed between lifting hand and turn angle, object height, and object weight. Additionally, significant nonlinear effects involving manipulation height were observed. For example, for the lifts with the contralateral hand, as shelf height increased equivalently (approximately 0.38*stature) between the low to middle shelf and the middle to high shelf conditions, the corresponding fore-aft distance between the lead foot and the load was observed to increase a distance (as a fraction of stature) of 0.012 and 0.053, respectively. For an individual with a stature of 175 cm, this associates to a change in the fore-aft lead foot placement of 2.1 and 9.3 cm between the low to middle and middle to high shelf conditions, respectively.

One potential reason for the lack of a meaningful relationship between object mass and behavior selection when the data presented here is grouped by hand may be attributed to the relatively small range of object masses manipulated throughout this experiment. Conversely, when the data is pooled, a larger absolute range of masses is included in the data for analysis suggesting mass may significantly contribute to the selection of behaviors. The limitations of the trial conditions associated with this experiment prevent a more detailed examination of the relationship between object mass and behavior selection.

One important observation from this study is that the foot placements associated with picking up and delivering objects are significantly affected by the direction in which
the worker will proceed following the object manipulation. For the most frequently observed behavior, turn angle affected all the lateral step distance measures, the foot orientation parameters, and select fore-aft step distance measures over the three steps necessary to manipulate the load and change the direction of progression. Step lengths during the behavior were not significantly affected by turn angle with the exception of the final step for contralateral handed lifts. For contralateral handed pickup transfers from a waist high shelf, if the turn angle is increased from about 15° to 180°, the lead foot orientation responds by rotating about 70° toward the direction of the turn. The change in orientation of the lead foot is accompanied by a lateral shift of the same foot toward the opposite direction of the turn equivalent to 0.13*stature (about a 23 cm shift for a 175-cm-tall individual).

The step length (1/stature) of the step prior to the terminal stance is not well predicted by any of the task or anthropometric measures. The only significant relationship is with BMI with higher BMI individuals taking slightly longer steps. However, the same measure for the step following the pickup is significantly affected by turn angle, pickup height, and stature in addition to BMI (for the contralateral handed lifts) and is predicted moderately well by those measures. One potential explanation for this apparent discrepancy may be attributed to the contribution of each of those steps toward positioning the body, and more specifically how participants transitioned between nominal walking to lifting or placing the object. For example, the final step length of the behavior (following the pickup or delivery) is the first in a sequence of steps along a new direction of progression. Large changes in this step length do not produce important changes in the distance to the next target, measured as a percentage of the total distance to the target. However, the first step length mentioned directly affects the placement of the lead foot, which is significantly affected by the task conditions. This suggests that the lead foot placement is the primary factor guiding foot placement prior to object manipulation and that the step lengths following object manipulation may be altered to accommodate the previous placement of the lead foot in the desired location. One question that still remains is whether the final step length absorbs all the residual distance to allow the lead foot to be in a certain location or if that distance is aggregated over a number of the previous steps. A statistical comparison between the preferred step length
during nominal gait and the steps prior to the lift may reveal more regarding how participants transition into these tasks.

The findings of this study are directly applicable to work cell layout design, particularly with respect to the required floor space necessary for operators to perform each of the five stepping behaviors presented here (further detailed in Chapter 4). Combined with estimates of nominal gait-step length models available in the literature (Grieve et al., 1966; Macellari et al., 1999; Stolze et al., 2000; Samson et al., 2001), the work here can be used also to define travel distances that may facilitate the selection of preferred stepping behaviors that would minimize the total number of steps and time. In addition, the results may be even more useful to ergonomic design situations if used as input to a whole-body manikin model, which can then be used to make design decisions that now would be based on more accurate ergonomic postural analysis.

Limitations

The two most frequently observed stepping behaviors across all the test conditions were two split stance behaviors with the contralateral foot as the lead foot. However, the prevalence of the contralateral lead foot behaviors may have been over represented, particularly for the pickup transfers, due to the experimental protocol. The same distance between the pickup tower and the start location was used for each trial for a particular subject. Additionally, the subjects were allowed to choose which leg to start stepping with at the beginning of each trial. It is possible that the subjects selected the leg that would facilitate a terminal stance with the contralateral limb as the lead foot. Although this strategy supports the hypothesis that certain stepping behavior patterns are preferred over others, for a work cycle that may include multiple transfers in sequence, operators may not have that same flexibility and be required to select another stepping behavior. The potential for over representing the contralateral lead foot behaviors is also supported by the observation that for the subset of trials in which the delivery distance was varied (i.e. equivalent to changing the start location for the delivery transfers), the frequency of ipsilateral lead foot behaviors was double that of the associated pickup trials. However, the contralateral lead foot behaviors still accounted for the majority of stepping behaviors in addition to different trial conditions, most noteworthy being transfer type and turn angles for the delivery transfers occurring over a larger range.
This study was conducted in a laboratory environment with one-handed cylinders and two-handed totes that are not representative of many of the hand-object coupling requirements in an industrial setting. Additionally, the load placement in the laboratory experiment was minimally constrained or obstructed by other parts or objects. However, comparison with the stepping behaviors observed in an industrial setting (Chapter 2) suggests that the set of stepping behaviors observed is consistent between the laboratory and assembly plant. Of more significant concern is the generalizability of these results to the manipulation of objects substantially heavier than the ones tested in the laboratory. The heaviest two-handed load in the laboratory was 13.61 kg, while the study in Chapter 2 revealed many operators lifting loads in excess of 30 kg. Further research is necessary to validate the results across a broader range of load conditions.

The effect of approach angle was not investigated here as a potential significant factor. Instead, turn angle, defined as the difference between the departure and approach angles, was used as the only potential regressor to account for the change in direction following the manipulation. For the one-handed trials, in which the object being manipulated was a vertical cylinder, the effect of approach angle on foot placement is most likely negligible due to the similarity across all approach angles with respect to the required hand/object coupling needed to lift the load. However, for two-handed manipulations in which the required orientations of the hands relative to the subject’s body change with the orientation of approach, approach angle could significantly affect the selection of foot placement. Unfortunately, approach angle was correlated with turn angle in the experimental design used here and the exclusion of approach angle in the analysis (particularly the regression models) was done to limit the problems associated with collinearity of regressors. The combined effects of approach angle and turn angle on foot position and orientation requires further investigation.

The most important restriction on these findings pertains to the subject pool recruited for the laboratory study. The participants of the laboratory study were recruited from the college student population and none of subjects had significant prior occupational manual material handling experience. However, the results presented here may still be applicable to experienced operators for similar lifting transfer tasks. A comparison of the stepping strategies used by experienced operators (Chapter 2) and the
participants in this study revealed similar trends in the most frequently observed behavior preference, although the differences in task conditions between the two studies limits the power of that assessment. Additionally, it was observed in the laboratory trials that the support foot during terminal stance of the most frequently observed stepping behavior was significantly oriented toward the delivery location, an attribute associated with experienced lifters (Authier et al., 1996). A ‘cross-over’ step behavior associated with experienced lifters (Delisle et al., 1999) also was observed in this lifting study. Although experience has been shown to affect lifting strategy for short distance transfers (Patterson et al., 1987; Mital, 1987; Gagnon et al., 1996), the same trends may not be as significant for transfers over larger distances. The potential benefit in balance suggested by Authier et al., (1996) resulting in experienced operators limiting the amount of pivoting while carrying the load may not be applicable for transfer distances that cannot be accomplished in one single motion. Additionally, if used in conjunction with a whole body model for potential design situations, foot placement strategies used by inexperienced lifters would result in an overestimation of traditional ergonomic stressors (i.e. moment at the low back) (Patterson et al., 1987; Gagnon et al., 1996) and introduce an additional safety factor for reducing potential hazardous lifting tasks.

3.8. Appendix

An example interpretation of the interaction plots used in this chapter is presented (Figure 3.22). The interaction plot shows the effect of one interaction term over the observed limits (min and max) of the other interaction term on the dependent measure of interest.
Figure 3.22. Example interaction plot for the dependent measure of step width ($X_i$) for the one-step ($S_iO_iC_{i+1}S_i$) stepping behavior depicted in Figure 3.7.A.
**Turn Angle by Hand Interactions, effects on q₂ and X₃**

![Figure 3.23](image-url)

Figure 3.23. Interaction plots for all significant interactions involving turn angle included in the final fit models for the one-step (S₁O₄C₁landingS₁) stepping behavior (see Figure 3.7.A). A) Q₂, lead foot orientation, B) X₃, final step width.

The interaction between turn angle and transfer hand is significant and included in both fit models for the Q₂ and X₃ parameters. For small turn angles, differences in the lifting hand(s) do not significantly affect the lead foot orientation (Figure 3.23.A). For example, the fit lines vary approximately over a 10° range in Q₂ spanning the different lifting hand(s) when the turn angle is less than 90°. However, for large turn angles, changes in lifting hand are more significant and can affect the lead foot orientation by over 30°. This interaction can potentially be explained by the kinematic constraints imposed by the lifting hand on the torso. For large turn angles, the external rotation range of motion about the hips may limit the capacity for both the lead foot to be oriented along the approach vector and the following step to be oriented along the departure vector. To compensate (assuming the same stepping behavior is being used), the lead foot can be internally rotated prior to placing it on the ground to effectively increase the amount of allowable turn by utilizing the full internal/external range of motion at the hip versus solely the range allowed during external rotation (i.e. as is the case if the lead foot is aligned with the approach vector). However, internally rotating the lead leg changes the neutral orientation of the whole body (particularly the torso) to face more toward the ipsilateral direction of the turn. For contralateral-handed lifts, the kinematics of the torso can remain in a neutral posture while the contralateral shoulder externally rotates to reach
the load, allowing for significant lead foot orientations. However, for lifts with the ipsilaterial hand, the torso must be recruited (specifically in twisting) to accommodate the reach, which may limit the benefit of large internal rotations of the lead foot in part due to the associated cost of twisting the torso.

The regression model for the step width of the last step \( (X_3) \) in the behavior also included a significant interaction effect between turn angle and lifting hand. The interaction trend (i.e. turn angle increases, step width decreases) was similar for all handedness conditions. However, for lifts involving the ipsilateral hand only, a greater range of step widths was observed than for lifts involving the contralateral hand only or both hands together. The large step width magnitudes for ipsilateral handed lifts followed by small turn angles may be largely attributed to the participants attempting to avoid the obstacle of the pickup shelf tower. The previous analysis demonstrated that for ipsilateral handed lifts, the lead foot position \( (X_2) \) is more contralateral than for the other handedness conditions. As such, a larger subsequent step width \( (X_3) \) is required to maneuver around the shelf tower to continue proceeding along a path close to the original direction of progression. For manipulations involving objects hanging from the ceiling (i.e. similar to the pneumatic tools observed in Chapter 2) where there does not exist an obstacle like the one described here, it is expected that the final step width would be more consistent across the lifting hand conditions.
Object Weight, Object Height, Turn Angle, and BMI Interactions

Figure 3.24. Interaction plots for the four interactions included in the final stepping parameter fit models for the S1C1B1S1 stepping behavior (see Figure 3.7.A). The interactions correspond to the contralateral handed lifts A) $q_1$, and B) $Y_3$ stepping parameters and the two handed lifts C) $X_3$, and D) $q_3$ stepping parameters.

The two significant interactions that entered the fit models for the contralateral-handed lifts occurred for the $q_1$ and $Y_3$ stepping parameters. The two interactions involved the same regressors of turn angle and pickup height. The $q_1$ fit model also includes a second order effect of pickup height, which is reflected in the interaction plots (Figure 3.24.A) by the nonlinear curves. For low pickup heights, the stepping parameter $q_1$ is fairly consistent across all ranges of turn angles, with the value of $q_1$ only varying by approximately 5 degrees over the approximately 90 degree range turn angle is varied. However, for pickups involving the higher shelves, which are associated with larger values of $q_1$ in general, the value of $q_1$ increases more significantly as turn angle increases. One potential explanation for this interaction may be attributed to the negative
correlation between the $q_1$ and $q_2$ stepping parameters (correlation coefficient of -0.2561 in this data). The stepping parameter $q_2$ is observed to vary over a larger range for higher pickups than lower ones with standard deviations of 30.8° and 17.8°, respectively. The same trend in $q_2$ is also observed with larger variations of $q_2$ being associated with larger turn angles. The standard deviations of $q_2$ for the 90° versus the 180° defined turn angles are 10.3° and 23.8°, respectively. The negative correlation between $q_1$ and $q_2$ suggests that the change in orientation of the body is aggregated, in part, between the first and second step orientations. As such, if the variations between $q_1$ and $q_2$ are equivalently aggregated, larger turn angles and pickup heights would be associated with a greater range of $q_1$ values as compared with the lesser values of the same regressors, which is what is observed in Figure 3.24.A.

An interaction between turn angle and pickup height is also observed for the $Y_3$ stepping parameter for the contralateral-handed lifts (Figure 3.24.B). At low pickup heights, the final step length ($Y_3$) is fairly consistent across all the turn angles at approximately 0.4 times stature. However, as pickup height increases, small turn angles are associated with only a slight decrease in step length while larger turn angles are associated a significant decrease in step length from approximately 0.41 to 0.31 times stature over the observed range of manipulation heights.

Figure 3.24.C depicts an interaction for the two-handed lifting trials for the $X_3$ stepping parameter between turn angle and object mass (scaled by body mass). For relatively light objects, the step width for small and large turn angle trials is fairly consistent. However, as object mass increases, smaller turn angles are associated with a slight increase in step width while larger turn angles are associated with a decrease in step width. This interaction plot suggests that step width is only significantly affected by object mass for large turn angles and affected by turn angle for larger object masses. If turn angle is interpreted as a variable that tests the internal/external range of motion about the hips, $X_3$ can be interpreted as a measure of success for that test. For example, if small positive values of $X_3$ are assumed to correspond to step widths similar to that observed for nominal straight line walking, smaller $X_3$ values could be interpreted as the residual amount of change in orientation still necessary to achieve straight line walking following the third step. As depicted in the interaction plot in Figure 3.24.C, the combined
conditions of heavier object mass and large turn angle could then be interpreted as a decrease in the available range of motion about the hips, potentially due to the increase in the moment of inertia of the combined body and load system.

The interaction between pickup height and BMI for the $q_3$ fit model for the two handed lifting trials is graphically depicted in Figure 3.24.D. This interaction is the only significant nonlinear effect included in any of the final fit models involving an anthropometric variable. The orientation of the final step is relatively constant for low shelf pickups for all individuals regardless of BMI with a value of approximately $-8^\circ$. However, for high pickup locations, as BMI increases, the angle of the final step relative to the departure direction increases significantly. The stepping parameter $q_3$ can be interpreted in a similar fashion as the $X_3$ stepping parameter was in the previous paragraph. Additionally, $q_3$ and $X_3$ are moderately correlated (correlation coefficient of 0.3183) suggesting that the similar interpretation is applicable. The interaction then may be potentially explained by the similar relationship as described for $X_3$ above. Since the load masses for this experiment were fixed, individuals with higher BMIs would result in lower percentage changes of total body plus mass moment of inertia. Following the interpretation above, we would expect then those individuals with higher BMIs to not be affected (with respect to the observed range of motion measured by the $q_3$ stepping parameter) as significantly as those subjects with lower BMIs, which are the trends that are observed in the interaction plots in Figure 3.24.D.
3.9. References


CHAPTER 4

THE TRANSITION STEPPING (TRANSIT) MODEL: PREDICTING ACYCLIC STEP PLACEMENTS USED DURING MANUAL MATERIAL HANDLING TRANSFER TASKS

4.1. Abstract

A Transition Stepping (TRANSIT) model based on the results of the laboratory experiment described in Chapter 3 is presented for predicting the foot placements used during manual material handling transfer tasks. The prediction has two parts. First, the stepping behavior, characterized by the LTRACS parameterization presented in Chapter 2, is predicted using a multinomial logistic regression model. Second, the step placements for the selected behavior, defined using the QTRACS parameterization presented in Chapter 3, are predicted using linear regression models based on the laboratory data. Five common stepping behaviors observed in both the industry study (Chapter 2) and laboratory study (Chapter 3) are modeled. The fit of the statistical models is evaluated in relation to the observed within and between-subject variance, and the overall model performance is evaluated across a wide range of task conditions. The median maximum error of the lead foot position for paired trials in which the most frequently observed behavior was performed was 7.5 cm. The within and between subject error for the same data were 4.8 cm and 7.8 cm, respectively.

4.2. Introduction

The analysis of materials handling tasks with digital human models (DHM) focuses on musculoskeletal loads associated with increased risk of acute or chronic injury, particularly at the low back and shoulder (Chaffin et al., 2006). The analyst using DHM software typically performs a static analysis of the most extreme posture that is
anticipated during a lifting or object placement operation (Stephens et al., 2006). The accuracy of the resulting analysis is strongly dependent on the accuracy of the posture (Delisle et al., 1998; Plamondon et al., 2006) yet current DHM software lacks validated posture prediction.

One critical component of the posture prediction is the foot placement. Because foot placement relative to the task strongly influences low-back and shoulder postures, inaccurate prediction of foot placement can result in a misleading analysis (Authier et al., 1996; Delisle et al., 1996; Burgess-Limerick et al., 1998; Wagner et al., 2006). Previous studies of materials handling have not focused on worker-selected foot placement in spite of its importance for prospective analysis (Delisle et al., 1999; Kollmitzer et al., 2002). Most MMH research over the past two decades has focused on modeling the internal distributions of muscle activation and tissue stress, with posture (including foot placements) as an input rather than an output (e.g., Buseck et al., 1988; Tsuang et al., 1992; Lavender et al., 2003). The analysis tools that have resulted from this work are of little value to practitioners unless they first have realistic posture data. If a workstation is already physically mocked up, data on postures can be obtained using video (Wrigley et al., 1991; Lowe, 2004), optical motion capture (Cook et al., 2007), or wearable technologies such as the lumbar motion monitor (Marras et al., 1992). However, the promise of proactive ergonomics can only be realized if analyses can be performed entirely in software, without physical mockups (Chaffin, 2005; Stephens et al., 2006; Wegner et al., 2007).

Another important limitation of most MMH research is that tasks are often performed in isolation, with the worker beginning the task already standing in front of the object to be manipulated. In real work scenarios (for example, the automobile assembly tasks described in Chapter 2), workers often lift and place objects as they move around a work area. The research in Chapter 3 demonstrated that the directions of approach and departure have a strong influence on foot placements during object interactions, so the context in which a task occurs is important. Moreover, the results of the field and lab studies presented in previous chapters demonstrate that the manipulation of many objects occurs with postures that are transient and probably not in static balance. For example, the most common foot movement pattern associated with object pickups includes only
one foot in contact with the ground at the time the object is picked up (Chapter 2). Previous MMH studies have not examined this behavior.

This chapter presents the Transition Stepping (TRANSIT) model, a behavior-based approach to modeling foot placements during materials handling tasks for use in DHM simulations. The model is designed to be used as a component of the more general model of ambulation presented in Chapter 5. The proposed TRANSIT model has two major components: (1) selection of a behavior, which is defined using the L-TRACS notation introduced in Chapter 2, and (2) scaling of the behavior using the results of the analysis presented in Chapter 3. The output of the model is a prediction of the position and orientation of the feet relative to the task for the five most common foot movement behaviors observed in the preceding laboratory study.

The chapter is divided into five major sections. First, inputs and outputs of the TRANSIT model are described and a block diagram depicting the flow of information is presented. Second, the first of the two TRANSIT sub-models that is used to predict an appropriate L-TRACS stepping behavior group from operator and task inputs is described in detail. Results of the behavior selection algorithm evaluated over a representative set of task conditions is presented. Third, the method for spatially scaling the predicted steps for each of the stepping behavior groups is illustrated. Individual regression models are presented for each step variable of each behavior group. Fourth, the performance of the model is evaluated for a variety of task conditions. The observed variability of subjects performing MMH transfer tasks from a laboratory study is compared with the residual error of select predicted step variables. Finally, implications of the results and observed limitations of the TRANSIT model are discussed.

4.3. Development of a Manual Material Handling Transfer Stepping Model

Model Inputs and Outputs

Model inputs are constrained to available data when analyses are performed for pro-active ergonomics assessments (i.e. a common application of digital human models where the TRANSIT model would be applied). The operator is characterized by gender, age, stature, and body mass. The task is defined by a representation of the required movement path defined by the transfer task (i.e. pickup, delivery, etc.), the specific location of the manual material-handling events (i.e. where the object to be picked up is
located), and relevant object properties (i.e. object mass, hand(s) necessary to manipulate the load). Straight-line paths between each of the transfer task locations are assumed to specify the relative locations of objects to handled. One pickup and one delivery task (in that order) are also assumed as an example manual materials handling task to be simulated. Figure 4.1 graphically depicts an example task for which the TRANSIT model could be used to predict foot placements. The input path points are defined as the start point (where the manikin starts with feet side by side), pickup location (where the pickup transfer occurs), delivery location (where the delivery transfer occurs), and the end point (where the manikin ends with feet side by side).

![Figure 4.1](image)

Figure 4.1. Graphical depiction of select task inputs and the subsequent positional output foot placement predictions for the TRANSIT model. A pickup and delivery transfer task similar to that presented in Chapter 3 is used as an example.

The cyclic step foot placement predictions between the path points in Figure 4.1 are simulated using an algorithm presented in Chapter 5. The TRANSIT model predicts
the foot placements at each of the transfer task locations that are affected by the object interaction, i.e., those steps that are different from normal gait steps. A method for integrating the two predictions is presented later in Chapter 5.

Figure 4.2 shows the flow of information for the Transition Stepping (TRANSIT) model. The inputs are the operator characteristics and the task requirements. The TRANSIT model is comprised of two empirical sub-models that, 1) selects a discrete stepping pattern by defining the number and type of steps to be scaled (Transition Behavior Selection shown in Figure 4.2), and 2) scales the foot placements for the behavior. A stepping Behavior Classification Library, which includes five commonly observed behaviors from the industry study (Chapter 2) and the laboratory study (Chapter 3), is passed as input to the Transition Behavior Selection model.

In the following sections, the two sub-models are described in detail, along with the overall flow of information throughout the TRANSIT model. To assess the performance of the TRANSIT model, predictions are evaluated against a subset of the data from the experiment presented in Chapter 3. The evaluation data were not used in the fitting of the MMH transfer stepping model parameters.
TRANSIT Model Data

The data used to develop the relationships described in the behavior selection and foot placement scaling sub-models were obtained in the laboratory experiment presented in Chapter 3. In the experiment, 10 men and 10 women performed a pickup and delivery transfer for each trial. Three object heights, three object masses (dependent on being a one or two handed lift), and three different turn angles for the pickup transfers were included. A subset of trials consisting of the 81 and 27 trials sets ($I_A$ trial group) and the 81 trial set ($I_B$ trial group) were used to develop the results presented here. Refer to
Chapter 3 for a more detailed description of the participants and the experiment from which the data were collected.

4.4. **Sub-Model 1: Selection of a Transition Behavior**

The Lexical Transition Stepping Classification System (L-TRACS) developed in Chapter 2 is believed to provide a concise notation for describing the sequence of foot movements associated with a transition. The L-TRACS nomenclature describes the configuration of the feet (parallel or split w/defined lead foot), in addition to the ground contact state of each foot during the terminal stance, which is interpreted here as the instance when the mass of the object is initially supported by the operator (pickup) or by the shelf (delivery). L-TRACS also describes the number of steps proceeding and succeeding that terminal stance, in addition to a qualitative descriptor associated with the movement of each step.

The stepping behaviors in the TRANSIT model include only a small subset of the kinematically feasible stepping behaviors available to an operator for performing a manual material handling transfer task. Conceptually, the range of stepping behaviors is infinite, but, as shown in Chapters 2 and 3, a small number of behaviors account for the vast majority of object interactions by both auto assembly workers and laboratory subjects. Five stepping behavior groups (see Chapter 2 for how behavior groups are formally defined) were selected and included in the Behavior Classification Library, from which behaviors are selected and used as predictions in the TRANSIT model. Table 4.1 defines these groups, which account for over 90% of all the stepping behaviors observed in an automotive assembly plant of operators performing MMH transfer tasks (Chapter 2) and over 71% of all the stepping behaviors observed in the laboratory experiment in which participants were asked to perform similar transfers (Chapter 3). Although only five behavior groups are included in the TRANSIT model, there potentially exist **270** different variations of those behaviors when considering the types of steps (see L-TRACS description in Chapter 2) and the potential ground contact states within each behavior group. Additionally, an infinite number of possible foot placement predictions are possible within each behavior variation due to the positions and orientations of the steps being modeled as continuous variables. A graphical depiction of the five stepping behavior groups is depicted in the next section.
Table 4.1. L-TRACS Behavior Groups Included in TRANSIT Model.

<table>
<thead>
<tr>
<th>Behavior Number (Order of Prevalence)</th>
<th>L-TRACS Codes*</th>
<th>Stance</th>
<th>Number of Departure Steps</th>
<th>Description</th>
<th>Short Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S₂C₁C₉ₛ₁</td>
<td>Contralateral Foot Forward</td>
<td>1</td>
<td>Split stance, contralateral foot forward, depart with an ipsilateral progression step</td>
<td>One-Step</td>
</tr>
<tr>
<td>2</td>
<td>S₂C₁C₉ₛ₁Oₛ₁C₁</td>
<td>Contralateral Foot Forward</td>
<td>2</td>
<td>Split stance, contralateral foot forward, depart with an ipsilateral orient step followed by a contralateral progression step</td>
<td>Two-Step</td>
</tr>
<tr>
<td>3</td>
<td>S₉ₛ₁C₁Oₛ₁Iₛ₁S₁</td>
<td>Ipsilateral Foot Forward</td>
<td>2</td>
<td>Split stance, ipsilateral foot forward, depart with contralateral foot orient step, followed by ipsilateral progression step</td>
<td>Ipsilateral Two-Step</td>
</tr>
<tr>
<td>4†</td>
<td>S₂O₂E₉ₛ₁Sc₁ṣ₁, S₉₂O₉ₛ₁S₁, S₂O₂E₉ₛ₁Sc₁, S₉₂O₂E₉ₛ₁S₁, S₂O₂E₉ₛ₁Sc₁ṣ₁</td>
<td>Even</td>
<td>1</td>
<td>Even stance, approached by either ipsilateral or contralateral foot first depart with a progression step from either step first. (Represented by ipsilateral departure step.)</td>
<td>Even</td>
</tr>
<tr>
<td>5</td>
<td>S₂C₁O₂Iₛ₁₉ₛ₁SC₁</td>
<td>Ipsilateral Foot Forward</td>
<td>1</td>
<td>Split stance, ipsilateral foot forward, depart with a progression step using the contralateral foot, stepping across the ipsilateral foot.</td>
<td>Crossover</td>
</tr>
</tbody>
</table>

* If more than one behavior is included in the Behavior group, the representative notation is shown in bold.
† Because the approach to an even stance can start with either the ipsilateral or contralateral foot, the subscripts 1 and 2 are used to indicate the first and second foot to arrive at the terminal (even) stance.

As part of a broader model of stepping behavior (see Chapter 5), the selection of an appropriate stepping behavior incorporates the positions of the steps from the previous component model and the requirements of the transfer task, in addition to operator characteristics. That is, the locations of the gait steps approaching the transition can affect the choice of behavior. However, the heuristics used to select a stepping behavior are implemented subsequent to an initial behavior ranking, and the two processes can be considered independent. Only the stepping behavior ranking based on a logistic regression model that relates task and operator characteristics to the likelihood of observing a behavior from each of the five major groups is presented here. The influence of the previous steps prior to the MMH transfer on behavior selection is discussed further in Chapter 5. The logistic model predicts the probability of a particular stepping behavior group given the transfer type, transfer hand(s), object weight*body mass, turn angle, manipulation height*stature, and the square of manipulation height*stature.

The analysis was performed using the JMP statistical software package (see jmpdiscovery.com). The logistic model fits probabilities of occurrence for the each of
the nominal responses (the five transition behavior groups in the case here). The formulation of the fit model takes the form:

$$\log \left( \frac{P(Y = j^{th} \text{ Nominal Response})}{P(Y = r^{th} \text{ Nominal Response})} \right) = X_j b_{nj}$$

where,

$Y$ is the set of $r$ (=5) transition behavior groups, $j$ ranges from 1 to $r-1$,

$X_j$ are the task and subject variables used to differentiate between the nominal responses,

$b_{nj}$ are the $n$ linear parameters corresponding to the $n X_j$ variables specified for the $j^{th}$ nominal response,

The model fits the $b_{nj}$ values to maximize the joint probability attributed by the model to the responses that occurred in the data. The fitting of the $b_{nj}$ parameters is equivalent to minimizing the negative log-likelihood as attributed by the model. The negative log-likelihood is given by:

$$-\text{loglikelihood} = -\log \left( P \left( \sum_{i=1}^{a} \text{row has the } Y_j^{th} \text{ Nominal Response} \right) \right)$$

where,

$a$ is the total number of experimental trials in the data (i.e. total number of rows)

The $b_{nj}$ parameters for the five nominal transition behaviors are presented in Table 4.2 along with summary statistics of the performance of the whole model fit. The formula derived from the logistic model to calculate probability of occurrence for the reference transition behavior (one-step, $S_1O_cC_{BB}S_1$) is given by:

$$P(S_1O_cC_{BB}S_1) = \left( 1 + \sum_{j=1}^{r-1} e^{X_j b_{nj}} \right)^{-1}$$

The subsequent probabilities, as referenced to the reference one-step transition behavior, are calculated using the following formula:

$$P(j^{th} \text{ Transition Behavior}) = P(S_1O_cC_{BB}S_1) * e^{X_j b_{nj}}$$
The logistic model used to predict the transition stepping behaviors based on task and subject conditions, summarized in Table 4.2, fits the data with an uncertainty coefficient U (similar to an $R^2$ measure for logistic models) of 0.18. Likelihood ratio tests were performed for each included model regressor and each was found to be significant with $p<0.0001$. The lone exception was object weight (% of body mass), which was significant at $p<0.0236$. A lack of fit test was also performed which calculated the probability that any higher order effects from the regressors currently included in the model would be statistically significant. The resulting probability of significance for including the additional effects was $p<0.999$, suggesting that any potential non-linear effects (composed of the included regressors), added to the current model, would not significantly improve the fit of the model from that presented in Table 4.2.

### Table 4.2. Stepping behavior group logistic model parameters with associated model performance measures*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$S_0C_{in}S_i$</th>
<th>$S_0C_{in}O_{sc}$</th>
<th>$S_0I_{in}O_{sc}$</th>
<th>$S_0E_{in}S_i$</th>
<th>$S_0I_{in}S_c$</th>
<th>Likelihood Ratio Test</th>
<th>Chi-Square</th>
<th>$p&gt;\text{ChiSq}$ (significance of effect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>†</td>
<td>0.0388</td>
<td>0.0148</td>
<td>-0.0120</td>
<td>-0.1588</td>
<td>395.2</td>
<td>p&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer Hand Both #</td>
<td>†</td>
<td>0.1094</td>
<td>0.2842</td>
<td>0.2108</td>
<td>0.0240</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer Hand Contralateral #</td>
<td>†</td>
<td>-0.1756</td>
<td>-0.8732</td>
<td>-0.3586</td>
<td>0.2237</td>
<td>20.2</td>
<td>0.0097</td>
<td></td>
</tr>
<tr>
<td>Transfer Hand Ipsilateral #</td>
<td>†</td>
<td>0.0662</td>
<td>0.59</td>
<td>0.15</td>
<td>-0.2478</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer Type Pickup #</td>
<td>†</td>
<td>-0.4109</td>
<td>-0.5807</td>
<td>0.3060</td>
<td>-0.9990</td>
<td>67.7</td>
<td>p&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Transfer Type Delivery #</td>
<td>†</td>
<td>0.4109</td>
<td>0.581</td>
<td>-0.306</td>
<td>0.9990</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manip. Height^2 ‡</td>
<td>†</td>
<td>2.8221</td>
<td>11.232</td>
<td>11.129</td>
<td>-20.028</td>
<td>48.9</td>
<td>p&lt;0.0001</td>
<td></td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients (columns) and the variable values, plus a constant intercept.

† Indicates the reference behavior to which all the other behavior probability of occurrences are referenced.

‡ Variable values included in the second order terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

# Transfer Hand and Transfer Type represent nominal variables and only one value from each group should enter the regression equation at any one time.
Although the logistic regression model demonstrates statistically significant effects, the data are dominated by the two primary behaviors independent of the potential predictors. Consequently, the primary effect demonstrated by the logistic model is a small shift in the probabilities of the two most-common behaviors. The model shows that the important choice of contralateral vs. ipsilateral lead foot is not determined primarily by the potential predictors considered here, since the predicted probabilities differ only slightly across the predictors. An in-depth examination of the data demonstrated that the selection of behavior is influenced to a greater extent by the preceding actions, as previously suggested. The effect of where the subject is in the gait cycle when entering the transition behavior discussed in further detail in Chapter 5. In particular, addressing this issue requires the more comprehensive approach to the prediction of work cell stepping presented in that section. However the relevance of the logistic model still applies to the behavior prediction problem as those additional criteria (i.e. where the subject is in the gait cycle) can be used to augment or exclude certain prediction probabilities of occurrence (and thus behaviors) that are calculated for each of the behavior groups.

Figure 4.3 graphically depicts the predicted probabilities from the logistic model for each of the five behaviors across 36 separate combinations spanning 4 turn angles, 3 transfer hand (contralateral, both, and ipsilateral) conditions, and 3 shelf heights. The predictions were calculated using an example operator picking up a 2.27 kg (one handed) or a 4.54 kg (two handed) load. The operator used for the predictions was 1800 mm in stature with a body mass of 71.28 kg. The shelf heights were scaled to 0.15, 0.53, and 0.9 times stature (equivalent to the laboratory experiment presented in Chapter 3). The crossover behavior (\(S_CO_I_{bb}S_c\)) is consistently predicted as the most probable behavior across all conditions involving the smallest 45° turn angle. The one step (\(S_OeC_{bb}S_I\)) behavior is predicted with the highest probability of occurrence for the 90° and 135° turn angle conditions regardless of the other task conditions. Similarly, the two-step (\(S_OeC_{bb}O_I_{bb}S_c\)) is the predicted by the logistic model as the most probable for the 180° turn angle condition regardless of the remaining task conditions. Although never predicted as the most probable, the even stance behavior is predicted with a 41.7% probability of occurrence for the two handed low shelf pickup transfer. The highest
probability of occurrence for the remaining ipsilateral two-step behavior occurred at 12.2% for the ipsilateral handed low shelf pickup condition.

Figure 4.3. Logistic model probability predictions for the five stepping behaviors across 4 turn angles, 3 shelf heights, and 3 hand conditions.

Figure 4.4 depicts the bivariate mosaic plot between the predicted behavior group (x-axis) and the observed transition behavior (y-axis) for the trials used in developing the model. The plot on the right in Figure 4.4 shows the observed behavior frequency. The plot on the left has the predicted behavior on the horizontal axis and the distribution of observed behaviors on the vertical axis. If the model were 100% accurate, the plot on the left would show a single-color vertical column for each behavior.

The even terminal stance behavior was predicted once for all the trial conditions, but incorrectly for the actual \(S_O C_{BB} S_I\) behavior. The 4-step ipsilateral lead foot behavior was not predicted at all. Not surprisingly, the \(S_C O_{BB} S_C\) crossover behavior was predicted even though it appeared infrequently in the data. This is potentially due to the large difference in mean shelf height and turn angle associated with that behavior group. The ipsilateral two-step behavior was correctly predicted 56.76% of the time with the remaining being predicted for trials in which the one-step \((S_O C_{BB} S_I)\) behavior was
observed. The one-step \( (S_O C_{BB} S_I) \) behavior was correctly predicted 86.36% of the time for trials in which that same behavior was observed. However, that same behavior was only predicted correctly 66.54% across all the trials. The two-step \( (S_O C_{BB} O_I S_C) \) behavior was predicted correctly 46.72% of the time it occurred in the data with the remaining instances being predicted as the most common one-step \( (S_O C_{BB} S_I) \) behavior. The most frequent behavior was observed for 56.94% of the trials and was predicted for 73.90% of the times. The second most frequent behavior was performed for 33.96% of the trials and was predicted 24.64% of the times.

![Bivariate plot of the transition behavior group multinomial prediction versus the observed experimental trials.](image)

Figure 4.4. Bivariate plot of the transition behavior group multinomial prediction versus the observed experimental trials.

### 4.5 Sub-Model 2: Spatial Scaling of the Transition Behaviors

The spatial scaling of each step position and orientation in each of the five transition behavior groups is presented in this section. Under the TRANSIT model information flow presented earlier in Figure 4.2, step scaling takes place after the selection of a behavior, which defines the number of steps to be taken with each foot and their sequence. The statistical approach to modeling the parameters defined for each behavior is similar to the analysis presented in Chapter 3. Each step in the transition
behaviors is parameterized using three variables, which are defined such that they can be roughly interpreted as a step width, step length, and step orientation measure. Each step is referenced with respect to the location of another foot placement and the current or future direction of progression. The single exception is the first predicted step placement, which is defined as the lead foot location during the terminal stance for split stance behaviors, and the center of the parallel stance for even stance terminal behaviors. The Q-TRACS parameterizations of the five modeled stepping behaviors are graphically depicted in Figure 4.5, Figure 4.6, and Figure 4.7.

Similar to the analysis performed in Chapter 3, each experimental trial was grouped using the associated L-TRACS nomenclature of the stepping behavior selected by the participant to facilitate a common set of variables for the prediction. Unfortunately, this grouping technique introduces an unbalanced design for the controlled independent measures used for the analysis. That is, because behaviors are to some extent influenced by body dimensions and test conditions such as shelf height, the distributions of these potential predictors within each behavior are skewed. However, the same trial conditions were presented to each participant and it is assumed that any skewness associated with each of the behavior specific data sets is encompassed with the behavior selection model previously described. To assess the possibility of overfitting, ten percent of the trials in each of the five behavior groups were randomly extracted and not used in the development of the model presented here. Those data are used for assessing the performance of the finalized model as described below. The frequency distributions of the subject number, object type (by hand), shelf height, and turn angle for each of the five transition behavior groups are presented below. The two most common transition behavior groups referred to as one-step and two-step (S_{OC}C_{BB}S_{I} and S_{OC}C_{BB}O_{I}S_{C}, respectively) were further partitioned by transfer type and handedness as suggested by the potential interactions presented in Chapter 3. Due to the limitations of the experiment and the number of trials associated with the remaining behavior groups (S_{OC}E_{BB}S_{I}, S_{OC}I_{BB}O_{C}S_{I}, and S_{C}O_{I}B_{BB}S_{C}), a similar partitioning was not possible and transfer type and handedness were included as potential nominal regressors in the stepwise regression formulations.
Figure 4.5. Q-TRACS parameterization and associated intervening variables used for scaling the one-step (SIOCBBCS1) and two-step (SIOCBBCOSC1) stepping behaviors.

Figure 4.6. Q-TRACS parameterization and associated intervening variables used for scaling the even stance (SIOCEnuS1 and SCOCEnuS1) stepping behaviors.
Figure 4.7. Q-TRACS parameterization and associated intervening variables used for scaling the ipsilateral two-step (S\textsubscript{c}O\textsubscript{I}BB\textsubscript{C}O\textsubscript{I}I\textsubscript{BB}C) and cross-over (S\textsubscript{c}O\textsubscript{I}BB\textsubscript{S}C) stepping behaviors.

**The $S_{O_{C}C_{BB}S_{I}}$ (#1: One-Step) Behavior Group**

The one-step ($S_{O_{C}C_{BB}S_{I}}$) behavior group was the most commonly observed stepping behavior group used during the transfer tasks and accounts for over 35.8% of all observations. The distribution of selected task and subject conditions for this behavior is presented in Figure 4.8. The results in Chapter 3 suggested that significant interactions between the type of transfer and the other task factor affect the step parameters of the one-step behavior group. As such, the one-step ($S_{O_{C}C_{BB}S_{I}}$) behavior group is further partitioned into six sub-groups consisting of transfers exclusively defined by contralateral-handed pickups, ipsilateral-handed pickups, two-handed pickups, and the same handedness conditions for the associated delivery transfer conditions. Rather than modeling the interactions with these variables, the simpler approach of building separate statistical models for each category was chosen.
Every participant in the laboratory study selected the SIOCs behaviour at least once. The same behavior was also the most frequent stepping behavior group utilized by a large number of participants (Figure 4.8). The behavior was also observed at least once for all test conditions. The behavior was observed primarily for moderate turn angle conditions (90° to 135°), however some subjects also used it for transfers requiring 180° turns.

Analysis of variance (ANOVA) was conducted for each of the stepping parameters in each of the six sub-groups this behavior group was observed. Multivariate regression was conducted to model any relationships and interactions between the subject and task factors of the transfer and the foot placement parameters. A two-step procedure for including potential regressors in the final fit model was used. First, an automated stepwise process utilizing mixed effects (i.e., forward/backward) with p<0.01 to enter and
p<0.05 to leave was performed. Second, an interactive procedure was performed to create more parsimonious models from those regressors automatically selected. A required increase in total adjusted $R^2$ for the model fit of 0.01 was used as a criterion for manually including a regressor. The resulting fit models and summary statistics for each of the step parameters predicted are presented in Table 4.3 through TG6.

In each of the summary tables for the pickup transfer tasks (i.e. Table 4.3, Table 4.4, and Table 4.5), nonlinear effects that included the manipulation height term were observed. The distance between the lead foot and the pickup location for the contralateral handed lifts was significantly affected by the square of the manipulation height term (Table 4.3). The observed trend was such that lifts from the high shelf resulted in the lead foot on average being 0.039*stature further away (measured along the approach vector) than for the lead foot placements observed for middle shelf transfers. Low shelf transfers resulted in the average lead foot placement being closer to the load by a difference of 0.017*stature when compared to the middle shelf transfers.

Across all the regression models, the lateral placement of the lead foot was best predicted. The RMSE for that step parameter, when compared with the other stature scaled step widths and lengths, was clearly the lowest. Turn angle was the most influential regressor on the lead foot lateral position with larger turn angles shifting the foot in the contralateral direction as defined with respect to the direction of the turn. Lead foot orientation was also well predicted ($R^2$ of 0.62 for contralateral handed pickups) by the regressors. However, the large remaining RMSE (17.2 degrees) suggests the variance of that step variable in the data set remains substantial.
Table 4.3. Regression equations predicting the step variables for the SO
C
M
S
stepping behavior in which the **contralateral hand** was used to **pick up** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X₁</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.205</td>
<td>-0.075</td>
<td>72.5</td>
<td>0.151</td>
<td>-0.302</td>
<td>-16.0</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-0.0017</td>
<td>-- †</td>
<td>-0.76</td>
<td>-0.0007</td>
<td>--</td>
<td>0.1232</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>0.68</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>0.0612</td>
<td>-0.0865</td>
<td>-18.9</td>
<td>--</td>
<td>--</td>
<td>-11.2</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>--</td>
<td>-0.0033</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.56</td>
</tr>
<tr>
<td>Manipulation Height² ‡</td>
<td>--</td>
<td>-0.1982</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height x Turn Angle ‡</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R² (adjusted)</td>
<td>0.63</td>
<td>0.39</td>
<td>0.62</td>
<td>0.25</td>
<td>0</td>
<td>0.38</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.037</td>
<td>0.043</td>
<td>17.3</td>
<td>0.032</td>
<td>0.098</td>
<td>6.299</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 4.4. Regression equations predicting the step variables for the SO
C
M
S
stepping behavior in which the **ipsilateral hand** was used to **pick up** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X₁</th>
<th>Y₂</th>
<th>q₂</th>
<th>X₃</th>
<th>Y₃</th>
<th>q₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.220</td>
<td>-0.133</td>
<td>34.1</td>
<td>0.070</td>
<td>-0.299</td>
<td>-23.3</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-0.0017</td>
<td>0.0007</td>
<td>-0.40</td>
<td>-0.0004</td>
<td>-- †</td>
<td>0.1272</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>0.0246</td>
<td>-0.0923</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-7.1</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>-0.0033</td>
<td>-0.0039</td>
<td>--</td>
<td>0.0035</td>
<td>--</td>
<td>0.59</td>
</tr>
<tr>
<td>Manipulation Height x Turn Angle ‡</td>
<td>-0.0016</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R² (adjusted)</td>
<td>0.54</td>
<td>0.34</td>
<td>0.35</td>
<td>0.31</td>
<td>0</td>
<td>0.32</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.034</td>
<td>0.045</td>
<td>11.8</td>
<td>0.024</td>
<td>0.102</td>
<td>5.7</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.
Table 4.5. Regression equations predicting the step variables for the $S_I O_C_{bb} S_I$ stepping behavior in which both hands were used to pick up a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.285</td>
<td>-0.244</td>
<td>59.2</td>
<td>0.201</td>
<td>-0.312</td>
<td>-9.1</td>
<td>0.074</td>
<td>0.183</td>
<td>7.5</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-0.0022</td>
<td>0.0007</td>
<td>-0.65</td>
<td>-0.0009</td>
<td>--†</td>
<td>0.1438</td>
<td>--</td>
<td>--</td>
<td>-0.1020</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height$^2$ ‡</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.3003</td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0.84</td>
<td>0.18</td>
<td>0.64</td>
<td>0.34</td>
<td>0</td>
<td>0.37</td>
<td>0.10</td>
<td>0.32</td>
<td>0.17</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.027</td>
<td>0.042</td>
<td>13.8</td>
<td>0.034</td>
<td>0.107</td>
<td>5.6</td>
<td>0.056</td>
<td>0.033</td>
<td>7.5</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 4.6. Regression equations predicting the step variables for the $S_I O_C_{bb} S_I$ stepping behavior in which the contralateral hand was used to deliver a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.029</td>
<td>-0.039</td>
<td>-30.8</td>
<td>0.033</td>
<td>-0.342</td>
<td>10.2</td>
<td>-0.018</td>
<td>0.229</td>
<td>8.9</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>--†</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.335</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>-0.0047</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.6252</td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.043</td>
<td>0.056</td>
<td>13.2</td>
<td>0.045</td>
<td>0.074</td>
<td>7.080</td>
<td>0.066</td>
<td>0.034</td>
<td>8.183</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
Table 4.7. Regression equations predicting the step variables for the SICCI stepping behavior in which the **ipsilateral hand** was used to **deliver** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_1$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_1$</th>
<th>$q_1$</th>
<th>$X_1$</th>
<th>$q_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.076</td>
<td>-0.013</td>
<td>-17.6</td>
<td>0.056</td>
<td>-0.371</td>
<td>8.1</td>
<td>-0.032</td>
<td>0.103</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.2571</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.0591</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.7e-04</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>-0.0082</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0</td>
<td>0.26</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.33</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.028</td>
<td>0.047</td>
<td>7.333</td>
<td>0.038</td>
<td>0.073</td>
<td>5.571</td>
<td>0.065</td>
<td>0.028</td>
<td>7.642</td>
<td></td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.

† A -- indicates that the model coefficient was not significantly different from zero.

Object mass (as a fraction of body mass) was not a significant factor in any of the step variable predictions except for one situation. Similar to the findings presented in Chapter 3, after scaling by body mass, object mass only significantly affected the fore-aft lead foot placement when pickup transfers were performed with the contralateral hand. Larger object masses resulted in shorter distances between the load and the lead foot. After scaling by stature, many of the variables were not significantly affected by any of the predictors and are modeled as constants. However, the positional variables still

Table 4.8. Regression equations predicting the step variables for the SICCI stepping behavior in which **both hands** were used to **deliver** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_1$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.024</td>
<td>-0.016</td>
<td>-22.6</td>
<td>-0.064</td>
<td>-0.339</td>
<td>14.4</td>
<td>-0.033</td>
<td>0.139</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0010</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.3437</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-10.1</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.5e-04</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>-0.0064</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>6.750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
<td>0.06</td>
<td>0</td>
<td>0.04</td>
<td>0</td>
<td>0.29</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.027</td>
<td>0.047</td>
<td>9.709</td>
<td>0.035</td>
<td>0.091</td>
<td>7.252</td>
<td>0.072</td>
<td>0.028</td>
<td>6.815</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.

† A -- indicates that the model coefficient was not significantly different from zero.
account for subject differences associated with body dimensions correlated to stature because of that scaling.

*The SiOCBBbO1SiC (##2: Two-Step) Behavior Group*

The SiOCBBbO1SiC behavior group was the second largest behavior group observed in the laboratory study, accounting for 23.9% of all transfer behaviors. As with the SiOCBBbO1SiC group, each subject executed this behavior at least once. Interestingly, approximately twice as many of the SiOCBBbO1SiC were observed for the high shelf transfers than was the case with the most common SiOCBBbO1SiC group (Figure 4.9). Also, although the SiOCBBbO1SiC behavior spanned all the turn angle conditions, the distribution of those turn angles suggests this behavior was selected primarily to re-orient the body over large angles. The subjects have similar terminal stances in the two behaviors, but in the SiOCBBbO1SiC behavior they reorient the trailing (ipsilateral) foot prior to taking a step away from the object pickup or delivery location.

Table 4.9 through Table 4.14 list the multivariate regression models constructed for each step parameter. Similar trends were observed for the lead foot placement of the terminal stance as described for the same foot in the SiOCBBbO1SiC behavior. Interestingly, only the step length variables (Y1) were observed to be significantly affected by the task and subject parameters for the contralateral handed deliveries utilizing this behavior (Table 4.12). However, the low R² values for those fit models suggest relatively weak effects. RMSE values of the step width variables, which were not significantly affected by any of the regressors, suggest that the null model sufficiently parameterized the foot positions in that dimension and that the variation in the data along those dimensions is relatively small.
Figure 4.9. Distribution of A) Subject Number, B) Manipulation Height, C) Object Type by Hand, and D) Turn Angle for the S_{ICBB}O_{SO} behavior group.
Table 4.9. Regression equations predicting the step variables for the $S_{O_{C}}C_{ba}O_{S_{C}}$ stepping behavior in which the contralateral hand was used to pick up a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Xₐ</th>
<th>Yₐ</th>
<th>qₐ</th>
<th>Xᵢ</th>
<th>Yᵢ</th>
<th>qᵢ</th>
<th>Xₜ</th>
<th>Yₜ</th>
<th>qₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.234</td>
<td>-0.153</td>
<td>58.2</td>
<td>0.134</td>
<td>-0.436</td>
<td>-35.0</td>
<td>0.182</td>
<td>-0.081</td>
<td>-28.0</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>-0.0015</td>
<td>-†</td>
<td>-0.5005</td>
<td>-0.0005</td>
<td>--</td>
<td>0.1483</td>
<td>-0.0009</td>
<td>0.0006</td>
<td>-0.2030</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>-0.0645</td>
<td>-22.9</td>
<td>0.0202</td>
<td>0.1585</td>
<td>--</td>
<td>--</td>
<td>-0.0591</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2.0e-04</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.8395</td>
<td>--</td>
<td>--</td>
<td>1.4291</td>
<td>-0.0028</td>
</tr>
<tr>
<td>Manip. Height²</td>
<td>--</td>
<td>-0.2489</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R² (adjusted)</td>
<td>0.40</td>
<td>0.18</td>
<td>0.39</td>
<td>0.19</td>
<td>0.16</td>
<td>0.31</td>
<td>0.11</td>
<td>0.32</td>
<td>0.20</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.042</td>
<td>0.043</td>
<td>16.0</td>
<td>0.027</td>
<td>0.102</td>
<td>7.0</td>
<td>0.055</td>
<td>0.045</td>
<td>13.266</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 4.10. Regression equations predicting the step variables for the $S_{O_{C}}C_{ba}O_{S_{C}}$ stepping behavior in which the ipsilateral hand was used to pick up a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Xₐ</th>
<th>Yₐ</th>
<th>qₐ</th>
<th>Xᵢ</th>
<th>Yᵢ</th>
<th>qᵢ</th>
<th>Xₜ</th>
<th>Yₜ</th>
<th>qₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.106</td>
<td>-0.265</td>
<td>17.3</td>
<td>0.187</td>
<td>-0.305</td>
<td>-0.37</td>
<td>0.297</td>
<td>-0.146</td>
<td>10.9</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>-0.0012</td>
<td>0.0007</td>
<td>-0.4143</td>
<td>-0.0006</td>
<td>--†</td>
<td>0.0637</td>
<td>-0.0017</td>
<td>0.0004</td>
<td>-0.2323</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>0.64</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>-0.0212</td>
<td>-0.0366</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2.32e-04</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height²</td>
<td>--</td>
<td>-0.2209</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height x</td>
<td>-0.0016</td>
<td>0.0021</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Turn Angle x</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R² (adjusted)</td>
<td>0.39</td>
<td>0.24</td>
<td>0.42</td>
<td>0.14</td>
<td>0</td>
<td>0.08</td>
<td>0.33</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.040</td>
<td>0.057</td>
<td>12.9</td>
<td>0.036</td>
<td>0.099</td>
<td>7.610</td>
<td>0.062</td>
<td>0.039</td>
<td>16.508</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.
Table 4.11. Regression equations predicting the step variables for the $S_{O_c}$C_{MB}O_{SC} stepping behavior in which both hands were used to **pick up** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
<th>$X_4$</th>
<th>$Y_4$</th>
<th>$q_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.290</td>
<td>-0.256</td>
<td>0.672</td>
<td>0.171</td>
<td>-0.307</td>
<td>0.53</td>
<td>0.051</td>
<td>0.022</td>
<td>-26.6</td>
<td>0.053</td>
<td>0.064</td>
<td>5.8</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>-0.0022</td>
<td>0.0009</td>
<td>-0.6685</td>
<td>-0.0006</td>
<td>--†</td>
<td>0.1087</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>0.18</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>-0.0458</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.97e-04</td>
<td>--</td>
<td>--</td>
<td>1.80e-04</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0.82</td>
<td>0.28</td>
<td>0.53</td>
<td>0.18</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
<td>0.36</td>
<td>0</td>
<td>0.18</td>
<td>0.22</td>
<td>0</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.027</td>
<td>0.046</td>
<td>16.424</td>
<td>0.035</td>
<td>0.100</td>
<td>8.168</td>
<td>0.056</td>
<td>0.042</td>
<td>12.836</td>
<td>0.039</td>
<td>0.047</td>
<td>8.686</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.

Table 4.12. Regression equations predicting the step variables for the $S_{O_c}$C_{MB}O_{SC} stepping behavior in which the **contralateral hand** was used to **deliver** a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
<th>$X_4$</th>
<th>$Y_4$</th>
<th>$q_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.031</td>
<td>-0.120</td>
<td>-23.2</td>
<td>0.058</td>
<td>-0.388</td>
<td>8.6</td>
<td>0.018</td>
<td>0.392</td>
<td>-25.3</td>
<td>-0.137</td>
<td>0.113</td>
<td>2.9</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>--†</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0020</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>-0.0922</td>
<td>--</td>
<td>--</td>
<td>0.0952</td>
<td>--</td>
<td>--</td>
<td>-0.1110</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<td>--</td>
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<td>--</td>
</tr>
<tr>
<td>Manip. Height$^2$ ‡</td>
<td>--</td>
<td>-0.5548</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$R^2$ (adjusted)</td>
<td>0</td>
<td>0.35</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>0.19</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>0</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.036</td>
<td>0.047</td>
<td>9.165</td>
<td>0.046</td>
<td>0.069</td>
<td>8.556</td>
<td>0.074</td>
<td>0.043</td>
<td>12.612</td>
<td>0.060</td>
<td>0.045</td>
<td>10.442</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.
Table 4.13. Regression equations predicting the step variables for the S_{O_{II}}C_{BB}O_{S_C} stepping behavior in which the *ipsilateral hand* was used to deliver a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X_2</th>
<th>Y_2</th>
<th>q_2</th>
<th>X_1</th>
<th>Y_1</th>
<th>q_1</th>
<th>X_4</th>
<th>Y_4</th>
<th>q_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.079</td>
<td>-0.448</td>
<td>-15.0</td>
<td>-0.144</td>
<td>-0.405</td>
<td>6.9</td>
<td>-0.063</td>
<td>0.131</td>
<td>-38.6</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0018</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.74</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>-0.0597</td>
<td>--</td>
<td>0.0920</td>
<td>--</td>
<td>-0.0124</td>
<td>-0.0651</td>
<td>12.2081</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>1.60e-04</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.40e-04</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m^2)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height^2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.4482</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R^2 (adjusted)</td>
<td>0</td>
<td>0.20</td>
<td>0</td>
<td>0.14</td>
<td>0.08</td>
<td>0</td>
<td>0.18</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.031</td>
<td>0.040</td>
<td>7.957</td>
<td>0.039</td>
<td>0.056</td>
<td>6.521</td>
<td>0.060</td>
<td>0.033</td>
<td>9.258</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regresor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
‡ Variable values included in the interaction terms were centered to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 4.14. Regression equations predicting the step variables for the S_{O_{II}}C_{BB}O_{S_C} stepping behavior in which *both hands* were used to deliver a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>X_2</th>
<th>Y_2</th>
<th>q_2</th>
<th>X_1</th>
<th>Y_1</th>
<th>q_1</th>
<th>X_4</th>
<th>Y_4</th>
<th>q_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.046</td>
<td>-0.627</td>
<td>-18.3</td>
<td>-0.171</td>
<td>-0.354</td>
<td>9.0</td>
<td>-0.031</td>
<td>0.399</td>
<td>-30.2</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0012</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>0.0364</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>2.55e-04</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m^2)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0036</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R^2 (adjusted)</td>
<td>0.82</td>
<td>0.28</td>
<td>0.53</td>
<td>0.18</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
<td>0.36</td>
<td>0</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.027</td>
<td>0.046</td>
<td>16.424</td>
<td>0.035</td>
<td>0.100</td>
<td>8.168</td>
<td>0.056</td>
<td>0.042</td>
<td>12.836</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regresor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.

*The S_{O_{II}}C_{BB}O_{S_C} (#3: Ipsi Two-Step) Behavior Group*

The next two stepping behaviors (S_{O_{II}}C_{BB}O_{S_C} and S_{O_{II}}C_{BB}O_{S}) account for approximately 4.3% of the total observed transfers. Handedness and transfer type were
included as nominal regressors for each of the analyses due to the limited number of available data points. Additionally, task conditions are unbalanced across each parameter (Figure 4.10 and Figure 4.11). The even stance behavior was primarily used for low shelf height transfers and clearly favored by a few individual participants (3, 9, and 17), who accounted for approximately half of the observed even stance transfers behaviors. The ipsilateral two-step (S_cO_tI_{bb}O_tS_c) behavior was more evenly distributed across the subjects, although five participants were never observed to use the strategy (participants 3, 8, 11, 15, and 18). Additionally, the contralateral hand transfers for that same behavior only accounted for a total of 13% of the observed trials within that behavior group.

The lateral step parameters of the first three steps of the ipsilateral two-step (S_cO_tI_{bb}O_tS_c) behavior all are observed to have relatively low RMSE (Table 4.15) subsequent to the fit model being applied (< 10% of stature for the displacement variables). However, only the lateral position of the second step in the behavior is well predicted by the regressors (R^2 = 0.75). This suggests the remaining lateral step parameters are adequately modeled by the null model parameterization, which takes into account most of the effects of turn angle. The relatively large RMSE of the fore-aft position of the first step with respect to the second (Y_t) indicates that the distance between the feet in the terminal split stance is highly variable even after the task effects are taken into account. This suggests that other factors may be contributing to the first step placement (see Chapter 5) when measured from the lead foot (second step).
Figure 4.10. Distribution of A) Subject Number, B) Manipulation Height, C) Object Type by Hand, and D) Turn Angle for the S\textsubscript{c}O\textsubscript{1}mmO\textsubscript{c}S\textsubscript{1} behavior group.
Table 4.15. Regression equations predicting the step variables for the $S_{O1}O_{II}O_{II}S_{I}$ stepping*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$X_1$</th>
<th>$Y_1$</th>
<th>$q_1$</th>
<th>$X_2$</th>
<th>$Y_2$</th>
<th>$q_2$</th>
<th>$X_3$</th>
<th>$Y_3$</th>
<th>$q_3$</th>
<th>$X_4$</th>
<th>$Y_4$</th>
<th>$q_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.278</td>
<td>-0.108</td>
<td>-3.8</td>
<td>-0.029</td>
<td>-0.043</td>
<td>12.1</td>
<td>-0.092</td>
<td>-0.496</td>
<td>-25.0</td>
<td>-0.030</td>
<td>0.351</td>
<td>21.4</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>-0.0015</td>
<td>-0.0005</td>
<td>-15.67</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Both #</td>
<td>-0.008</td>
<td>0.024</td>
<td>0.967</td>
<td>-0.003</td>
<td>0.046</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Contralateral #</td>
<td>0.065</td>
<td>0.008</td>
<td>8.527</td>
<td>-0.020</td>
<td>0.009</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>6.327</td>
</tr>
<tr>
<td>Transfer Hand Ipsilateral #</td>
<td>-0.057</td>
<td>-0.032</td>
<td>-9.494</td>
<td>0.023</td>
<td>-0.055</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Type Pickup #</td>
<td>0.025</td>
<td>0.019</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.039</td>
<td>0.016</td>
</tr>
<tr>
<td>Transfer Type Delivery #</td>
<td>-0.025</td>
<td>-0.019</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.047</td>
<td>--</td>
<td>0.039</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>4.08e-04</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.0030</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$Y_1$ (previously predicted step parameter)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

$R^2$ (adjusted) 0.75 0.47 0.20 0.26 0.30 0.54 0.51 0.23 0.35 0.43

Root Mean Square Error 0.034 0.038 12.476 0.032 0.096 5.867 0.034 0.082 16.719 0.070 0.038 7.650

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero
# Transfer Hand and Transfer Type represent nominal variables and only one value from each group should enter the regression equation at any one time.

The $S_{I}O_{2}E_{III}O_{II}$ (#4: Even-Stance) Behavior Group

Transfer hand, transfer type, and turn angle entered as regressors for most of the $S_{I}O_{2}E_{III}O_{II}S_{I}$ step parameters (Table 4.16). Interestingly, the stance width was not well predicted by any of the task or subject variables. The relatively low RMSE of the stance-width parameter $W_2$, suggests that the terminal stance width did not significantly vary in the data after being scaled by stature, so there was little variance to predict. This observation is somewhat limited in that three subjects accounted for a majority of the behavior group and that self-selected stance width can be interpreted as akin to a body dimension. The lateral position of the center of the even stance was well predicted by the transfer hand, transfer type, and turn angle ($R^2$ of 0.79). The similar RMSE of the foreaft position of the same point suggests a comparable amount of variance in the data subsequent to the prediction even though the regressors are not as strongly related ($R^2 = 0.27$).
Figure 4.11. Distribution of A) Subject Number, B) Manipulation Height, C) Object Type by Hand, and D) Turn Angle for the S\textsubscript{1}O\textsubscript{2}E\textsubscript{in}S\textsubscript{1} behavior group.
Table 4.16. Regression equations predicting the step variables for the even \( S_{O_{2}}E_{mm}S_{1} \) stepping behavior*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>( X_{1} )</th>
<th>( Y_{1} )</th>
<th>( W_{1} )</th>
<th>( q_{1} )</th>
<th>( q_{2} )</th>
<th>( X_{3} )</th>
<th>( Y_{3} )</th>
<th>( q_{3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.288</td>
<td>0.033</td>
<td>0.108</td>
<td>-28.9</td>
<td>42.6</td>
<td>0.113</td>
<td>0.402</td>
<td>2.5</td>
</tr>
<tr>
<td>Turn Angle (deg.)</td>
<td>-0.0021</td>
<td>--†</td>
<td>--</td>
<td>0.2455</td>
<td>-0.3692</td>
<td>-0.0009</td>
<td>--</td>
<td>-0.1225</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manip. Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-20.0</td>
<td>--</td>
<td>-0.0635</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Both #</td>
<td>0.008</td>
<td>0.027</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Contralateral #</td>
<td>0.048</td>
<td>-0.010</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Ipsilateral #</td>
<td>-0.056</td>
<td>-0.017</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Type Pickup #</td>
<td>0.023</td>
<td>0.013</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.045</td>
<td>0.016</td>
<td>6.719</td>
</tr>
<tr>
<td>Transfer Type Delivery #</td>
<td>-0.023</td>
<td>-0.013</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.045</td>
<td>-0.016</td>
<td>-6.719</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>-1.33e-04</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( R^{2} ) (adjusted)</td>
<td>0.79</td>
<td>0.27</td>
<td>0</td>
<td>0.17</td>
<td>0.40</td>
<td>0.21</td>
<td>0.17</td>
<td>0.31</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.032</td>
<td>0.039</td>
<td>0.024</td>
<td>11.823</td>
<td>15.488</td>
<td>0.075</td>
<td>0.040</td>
<td>8.645</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† -- indicates that the model coefficient was not significantly different from zero.
# Transfer Hand and Transfer Type represent nominal variables and only one value from each group should enter the regression equation at any one time.

The \( S_{C}O_{1}I_{BB}S_{C} \) (#5: Crossover) Behavior Group

The fifth behavior group was observed 43 times (out of 4494 trials) when all the \( I_{A} \) and \( I_{B} \) experiment trials were considered (Figure 4.12). The small number of times this behavior was observed suggests it may not be the preferred stepping pattern under any combination of task conditions, but utilized only when the pre-transition preparation has been insufficient to enable a preferred behavior. The behavior is characterized by a somewhat awkward “crossover” step, in which the contralateral foot steps across the ipsilateral lead foot. Delisle et al. (1999) identified a similar ‘cross-over’ strategy to be associated with expert material handlers. Delisle suggested that the benefits of such a strategy included the ”reduction in the asymmetry of posture at the deposit” location, which was observed for transfer tasks requiring less than 2 steps between the pickup and delivery. Since the transfers studied here involved larger delivery distances than those observed by Delisle et al. (1999), this proposed benefit was probably not a primary factor in the selection of this behavior for the participants in the current study. Few participants
were willing to perform this riskier maneuver (defined in the context of increasing the chance of a fall due to the contralateral foot potentially hitting the ipsilateral support limb during the second step), as opposed to taking an additional step (for example, moving out of the ipsilateral-foot-forward terminal stance with a ipsilateral two-step \((S_C O_I b b O_C S_1)\) behavior, in which the first step after the object manipulation is an orient step with the contralateral foot, rather than a progression step). One subject (number 4) accounted for nearly half of the observations this behavior was used. In addition, nearly all the transfers when this behavior was selected were manipulations from the middle shelf height.

The spatial variables of the final two steps of the crossover \((S_C O_I b b S_C)\) behavior group are well predicted by the task and subject parameters \((R^2 \geq 0.53\) for all cases). Additionally the RMSE is fairly consistent across variables (Table 4.17), suggesting that these steps contribute fairly equivalently to the variability of the spatial aspect of the behavior. Similar to the previous behaviors, the first step length is not well related with the subject and task factors, suggesting that the foot spacing in the terminal stance (relative placement of the first two steps of the behavior) is affected primarily by factors other than those examined here. Neither the lateral or fore-aft position of the first step (measured with respect to the second, i.e., the trailing leg at terminal stance) was significantly affected by any of the potential regressors.
Figure 4.12. Distribution of A) Subject Number, B) Manipulation Height, C) Object Type by Hand, and D) Turn Angle for the S_{ci}O_{hi}S_{ci} behavior group.
Table 4.17. Regression equations predicting the step variables for the S_{OI}I_{BB}S_{C} stepping behavior in which
the contralateral hand was used to pickup a load*.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(X_1)</th>
<th>(X_2)</th>
<th>(X_3)</th>
<th>(q_1)</th>
<th>(q_2)</th>
<th>(q_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.265</td>
<td>-0.100</td>
<td>11.5</td>
<td>-0.144</td>
<td>0.319</td>
<td>4.4</td>
</tr>
<tr>
<td>Turn Angle (degrees)</td>
<td>-0.0016</td>
<td>-0.0011</td>
<td>--(^\dagger)</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Object Mass (fraction of body mass)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Manipulation Height (fraction of stature)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Transfer Hand Both #</td>
<td>-0.001</td>
<td>0.002</td>
<td>-2.27</td>
<td>--</td>
<td>--</td>
<td>0.782</td>
</tr>
<tr>
<td>Transfer Hand Contralateral #</td>
<td>0.048</td>
<td>0.023</td>
<td>6.78</td>
<td>--</td>
<td>--</td>
<td>-3.095</td>
</tr>
<tr>
<td>Transfer Hand Ipsilateral #</td>
<td>-0.047</td>
<td>-0.026</td>
<td>-4.51</td>
<td>--</td>
<td>--</td>
<td>2.313</td>
</tr>
<tr>
<td>Transfer Type Pickup #</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.025</td>
</tr>
<tr>
<td>Transfer Type Delivery #</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-0.025</td>
</tr>
<tr>
<td>Stature (mm)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Body Mass Index (kg/m(^2))</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>(R^2) (adjusted)</td>
<td>0.71</td>
<td>0.58</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
<td>0.11</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.049</td>
<td>0.042</td>
<td>13.62</td>
<td>0.050</td>
<td>0.071</td>
<td>5.694</td>
</tr>
</tbody>
</table>

\* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of
the products of the coefficients and the variable values, plus a constant intercept.
\(^\dagger\) -- indicates that the model coefficient was not significantly different from zero.

# Transfer Hand and Transfer Type represent nominal variables and only one value from each group should
enter the regression equation at any one time.

4.6. Model Performance

The processes and criteria for evaluating the performance of the TRANSIT model
are potentially complex, but should take into account the intended use and final
implementation of such a model. The TRANSIT model contains two primary sub-
models described above, including several dozen regression equations predicting
particular degrees of freedom, with different sets of equations used for different
behaviors. In considering how well the model as a whole performs, several principles are
identified.

1. The TRANSIT should qualitatively reflect the relationships known or
previously examined (see Chapter 3) that exist between subject and task factors, and the
predicted foot placements.

2. The model should predict reasonable step placements for task conditions
spanning a large range of potential task analyses, both within and beyond the range of the
data used to generate the model. That is, the model should interpolate smoothly and “fail
soft.”

3. The model should do as good a job as possible of predicting the most
important variables, (i.e. the lead foot placements). To this end, the model has been
constructed so that lead foot placements are predicted directly from task variables,
whereas other foot placements are predicted from the lead foot placement.

4. The model performance should be compared with the within- and between-
subject variability. In general, the model cannot predict better than within-subject
variability, and cannot take into account between-subject variability that is unrelated to
the variables used to characterize the worker.

Qualitative Evaluation

As a first step in evaluating the model performance, the model behavior was
examined over a range of independent measures. The effect of handedness and turn
direction on predicted pickup transition step placements are depicted in Figure 4.13.
Four turn angles (45°, 90°, 135°, and 180°) are and three lifting hand(s) conditions are
examined for two different split stance lead foot conditions. A similar trend in which the
contralateral, both, and ipsilateral handed pickup conditions are associated with
increasing shifts, respectively, in the lateral foot position of the lead foot toward the
contralateral direction (as defined by the turn direction) was also observed by Wagner et
al. (2005). The contralateral shift of the lead foot placement (and corresponding steps)
exhibited by the TRANSIT model as turn angle was increased was also observed in the
data presented in Chapter 3. In nearly all the predicted situations, with the exception of
the 180° turn condition in which the one-step ($S_t O C_{BB-S_i}$) behavior was used, the
predicted lead foot placement for the ipsilateral handed lift was always further
contralateral than the two-handed pickup predicted condition.
Figure 4.13. Example of the transition behavior selection and scaling as a function of turn angle (contralateral lead foot).

To exercise the complete model, including the selection of the behavior, the complete walk-pickup-deliver-return task sequence was simulated (see Chapter 5 for details of how the gait strides are simulated). Initial foot positions and the pickup location were fixed while the location of the delivery tower was varied, effectively changing the turn angle at the pickup transfer. The positions of the delivery tower were
selected such that the pickup transfer turn angle ranged from 45° to 180° in 1° increments. Ipsilateral, contralateral, and two-handed transfers were simulated over the complete range of angles. An initial position was selected such that a contralateral lead foot behavior would be preferred. A summary of the results is depicted in Figure 4.14. The one-step ($S_O C_{BB} S_i$) transition behavior is predicted for small turn angles. Increasing the turn angle starting at 45° resulted in a corresponding increase in probability calculated by the logistic model for the two-step departure ($S_O C_{BB} O_i S_C$) behavior, which became the most likely behavior for all the transfer hand conditions between 110° and 120°. The two-handed condition transitioned into predicting the two-step departure behavior first (at the lowest turn angle), followed by the right hand transfer, which was then followed by the left handed transfer at a turn angle between 119° and 120°.
Figure 4.14. Example of the transition between contralateral lead foot behaviors for left, right, and both handed transfers as a function of turn angle. The lines defined by $B'$ and $B''$ depict the turn angles for each handedness condition for which the change between the one-step and two-step behavior occurs.

Quantitative Model Evaluation Using Repeated Trial Data

A certain amount of natural variability in human motion is inherent even in planned, volitional movements. As such, perfect correspondence between observed and predicted movements is not to be expected. One aspect of the challenge in evaluating the performance of the model is that comparisons of foot placements must be made within behavior, and participants exhibited a range of behaviors, even during similar trials. The most useful data for evaluating within- and between-subject variance were obtained in a subset of the I\textsubscript{A} trial-set data. In these trials, all with medium-weight loads, the turn angle was held constant at 135 degrees. The only manipulation across six conditions was variation in the distance between the pickup and delivery towers. Because the potential
influence of the delivery distance on the pickup behavior decreases as the distance increases, the two trials with largest distance (approximately four gait steps away) were considered to be repeated trials with respect to the pickup. Three handedness conditions (ipsilateral, contralateral, and both) also were considered.

Seventeen of the 20 participants produced the dominant one-step departure behavior \( S_{0CBB} \) in both trials for at least one handedness condition. Twelve of the seventeen used the same behavior for paired trials in two handedness conditions. Nine and fourteen of the subjects used the same behavior for paired trials in the ipsilateral and contralateral handedness conditions, respectively. Six subjects produced paired trials in all three handedness conditions (six total trials for each subject). All together, thirty-five pairs of trials with the same behavior, for the same handedness condition, were extracted for analysis.

Within-subject variance (reported as standard deviation) for each step variable was calculated for each handedness condition. Although similar values were observed between the conditions, the contralateral pairings are reported because most of the subjects were involved in that pairing condition. The median of the differences in Euclidean distance and foot orientation between all paired trials also was calculated as a measure of within-subject error. The within-subject variance is intended to be compared directly to the RMSE values in each of the models previously developed. The within-subject error is used as a measure of model performance for comparing model predictions to a subset of trials with the same input conditions (referred to as the “comparison set”). The subset of trials was not used in the development of the model regressions. These within-subject measures can be interpreted as a lower bound for any model predictions as the model cannot be expected to perform better than the natural variability observed within the participants. Table 4.18 summarizes the within subject error and variance for each step variable.

The between subject variance was calculated using the same 28 contralateral handed transfer trials. The difference between each of the step variables for the 70 trials and the associated average values for that handedness trial condition were computed. Those differences are the deviation (measured in cm and degrees) between subjects performing the same transfer tasks and are reported in Table 4.18 as a measure of
between-subject error. The between-subject variance includes the effects of body dimension and subject preference. For the lead foot lateral placement step variable \((X_2)\), the between-subject variability was slightly less (6.25%) than the within-subject variability. This is potentially caused by the small number of paired trials used to calculate these measures.

The RMSE for the predicted pickup transfer step variables for the same one-step behavior as the paired data are repeated in Table 4.18 for reference. The RMSE of the lead foot lateral placement \((X_2)\) for the model predictions pertaining to the three handedness is approximately twice that of the within subject variance. The between subject variance is similar to the within subject variance (actually lower by a small amount) suggesting that the residual variance not accounted for by the model predictions is related to the variability of the task. The RMSE of the lead foot fore-aft position \((Y_2)\) for the model predictions is approximately twice that of the within subject variance and about 15% larger than the between subject variance. Comparing the between and within subject variances suggests that there exists a significant subject preference and/or associated anthropometric effect. The one handed models for the \(Y_2\) step variable include body mass index as a significant effect while the two handed condition does not include any significant body effect. Lead foot orientation for the contralateral handed prediction model is slightly larger than the between subject variance, which is equivalently larger than the within subject variance. Although the ipsilateral and two handed model seem to perform well when compared to the contralateral within subject variance measure, previous data and the discrepancy in lead foot orientation between the handedness conditions suggest that the equivalent within subject variation for those different handedness transfers also are smaller.
Table 4.18. Within subject variance and maximum median error in predicting the position of the toe and angle of the foot for the three steps of the $S_tO_cC_{mb}S_t$ transition behavior group.

<table>
<thead>
<tr>
<th></th>
<th>Step 1</th>
<th>Step 2 (Terminal stance lead foot)</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Positional (cm)</td>
<td>Ang. (deg)</td>
<td>Positional (cm)</td>
</tr>
<tr>
<td>Within Subject Error</td>
<td>6.5</td>
<td>2.1</td>
<td>4.8</td>
</tr>
<tr>
<td>(paired data)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Between Subject Error</td>
<td>21.6</td>
<td>3.0</td>
<td>7.8</td>
</tr>
<tr>
<td>(paired data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Model Error</td>
<td>19.0</td>
<td>3.8</td>
<td>7.5</td>
</tr>
<tr>
<td>(paired data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Model Error</td>
<td>19.3</td>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>(all validation $S_tS_cC_{mb}S_t$ data)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Positional (fraction of stature)</th>
<th>q_1 (deg)</th>
<th>Positional (fraction of stature)</th>
<th>q_2 (deg)</th>
<th>Positional (fraction of stature)</th>
<th>q_3 (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within Subject</td>
<td>0.024</td>
<td>0.091</td>
<td>4.0</td>
<td>0.016</td>
<td>0.021</td>
<td>11.8</td>
</tr>
<tr>
<td>standard deviation</td>
<td>(paired data)</td>
<td></td>
<td>(paired data)</td>
<td></td>
<td>(paired data)</td>
<td></td>
</tr>
<tr>
<td>(paired data)</td>
<td>0.024</td>
<td>0.128</td>
<td>4.8</td>
<td>0.015</td>
<td>0.038</td>
<td>14.9</td>
</tr>
<tr>
<td>*RMSE for the</td>
<td>0.032</td>
<td>0.098</td>
<td>6.3</td>
<td>0.037</td>
<td>0.043</td>
<td>17.3</td>
</tr>
<tr>
<td>contralateral hand</td>
<td>pickup predictions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*RMSE for the</td>
<td>0.034</td>
<td>0.107</td>
<td>5.6</td>
<td>0.027</td>
<td>0.042</td>
<td>13.8</td>
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<tr>
<td>two handed pickup</td>
<td>predictions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*RMSE for the</td>
<td>0.024</td>
<td>0.102</td>
<td>5.7</td>
<td>0.034</td>
<td>0.045</td>
<td>11.8</td>
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<tr>
<td>ipsilateral hand</td>
<td>pickup predictions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† The paired data includes 14 subjects performing the same pickup transfers with the contralateral hand.
*RMSE values are repeated from the one-step ($S_tO_cC_{mb}S_t$) behavior predictions for the contralateral, both, and ipsilateral handed pickup transfer models presented in Section 4.5.

The median errors presented at the top of Table 4.18 also are a measure of within- and between-subject performance. The relatively small difference between the terminal stance lead foot (step 2) between and within subject error measures supports the previous assertion that the lead foot placement for this split stance behavior is critical across participants and that subject differences (although present) have a relatively minor effect on the lead foot placement.
Comparatively, the between subject error of 21.6 cm for the first step in the $S_1O_cC_{bb}S_1$ behavior group is significantly larger than the associated within subject measure of 6.5 cm. This can potentially be explained by the previously suggested step scaling strategy of altering the step length of the final step (step 2) to accommodate the lead foot position based on where in the gait cycle the position of the lead foot landed. As expected, the lead foot position as referenced to the gait cycle, would be similar for the same subject starting in the same place. It would be, however, significantly different across subjects with different nominal gait strides.

Quantitative Model Evaluation Using Select Laboratory Trials

The comparison of within and between subject variances to the RMSE model predictions previously documented are useful for directly comparing the developed models to the natural variability of the operators. However, the different task conditions for which the prediction models were developed (as compared to the single task condition evaluated for determining the within and between subject variation) make directly assessing the performance of the model over those varied task conditions ambiguous. A similar difficulty also exists for comparing the model performance for different behavior step predictions. To address this issue, the TRANSIT model was used to predict the step placements for the pickup transfers of the paired data and also for select laboratory trials. The comparison laboratory trial data set consisted of 10% of the laboratory trials, randomly selected, from which each of the five transition behaviors was observed. Those 10% of trials were not used to develop the model parameters and are used here to compare the TRANSIT model error (within behavior) to the previously defined within and between subject error measures.

The median error between each of the paired data trials and the TRANSIT predictions were calculated for the one-step ($S_1O_cC_{bb}S_1$) behavior. The median positional errors for the first, second and third, steps was 19.0, 7.5, and 15.9 cm respectively. The median error for the first two steps was less than the between subject median error suggesting that the inclusion of the body dimensions within the TRANSIT model to aid in the predictions accounts for some of the variability between subjects. The median error of the first step (19.0 cm) associated with the TRANSIT model is potentially overestimating the error associated with that step. As previously suggested, this error is
dependent on the predicted gait stride of the individual, a model separate from the TRANSIT formulation. Due to the differences in nominal stride length between the observed subjects and predicted values, the first predicted step position used to evaluate the error was defined to be independent of the initial location because there was no guarantee that the predicted gait stride length would result in a contralateral lead foot transition behavior being selected. The median error of 8.5 cm was observed for the lead foot predictions of the TRANSIT model over all the observed S\textsubscript{O}\textsubscript{CCBB}S\textsubscript{I} trials. This value is not significantly larger than the paired data set median error of 7.5 cm, suggesting that the TRANSIT model is accounting for the additional variability in step position due to the different task factors.

The comparison data set included 10\% of the laboratory trials observed for each of the five predicted behavior groups. The TRANSIT was used to predict foot placements for each of the trials within the comparison data set. Figure 4.15 plots each of those stepping behaviors and overlays the error between the predictions and the laboratory trial data. Similar to the S\textsubscript{O}\textsubscript{CCBB}S\textsubscript{I} behavior, the lead foot in each of the behavior groups was best predicted as depicted by the least amount of scatter surrounding that step in Figure 4.15. As a comparison to the error plots in Figure 4.15, the foot placements observed for each behavior and used to construct the regression equations for each step variable (from the laboratory study in Chapter 3) are plotted in Figure 4.16. The foot placements are reoriented such that the manipulation location is the same for all trials. No other scaling is used. The ball of the foot for each step is depicted as a unique color (defined in Figure 4.16).
Figure 4.15. Predicted error for the foot placement prediction for the A) $S_1O_1C_{BB}S_I$, B) $S_1O_2C_{BB}O_1S_C$, C) $S_1O_2E_{BB}S_I$, D) $S_1O_1I_{BB}O_1S_I$, and E) $S_1O_1I_{BB}S_C$ transition behavior groups.
A new method for the analysis and simulation of foot stepping behaviors in manual materials handling tasks has been developed. The resulting Transition Stepping (TRANSIT) model for predicting the acyclic foot placements associated with those behaviors has been presented. A classification of foot behaviors developed from observations of workers (L-TRACS) provided the basis for categorizing the transition
stepping behaviors (Chapter 2). Data from a laboratory study illustrated that five behaviors accounted for over 71% of the observed foot behaviors. From these results, the TRANSIT model uses task and human characteristics to select appropriate L-TRACS behaviors, and then scales the foot placement positions and orientations using statistical regression models developed from laboratory data.

This work has provided evidence that a person can perform a task with a wide variety of different foot movement patterns. More importantly, the data from the laboratory study (Chapter 3) has shown that for tasks where an individual has an accurate knowledge of the environment, particularly for well-learned and practiced jobs, there exists a meaningful consistency of stepping behaviors within and between individuals. Furthermore, these stepping progressions can be represented by a concise set of scalable behaviors that comprise a majority of those observed in common MMH jobs.

The logistic model used to predict the L-TRACS behavior included effects for transfer type, transfer hand(s), object weight*body mass, turn angle, manipulation height*stature, and the square of manipulation height*stature. Statistically significant effects (p<0.05) were observed for all of the subject and task factors. However, the only relevant task factor associated with the most likely predicted behavior (i.e. largest probability of occurrence among the five behavior groups) was turn angle. Changes in the remaining task factors were not as clearly associated with definitive behavior selection or exclusion. One potential explanation of this result is that the behavior groups presented in Chapter 2 are too general and may encompass too many individual behaviors to be distinguished with the select task factors used in the laboratory. Another possibility is that the laboratory task conditions did not vary over a large enough range to significantly drive the behavior selection process. This possibility is supported from a result presented in Chapter 3, which showed four out of the five transition behavior groups (excluding the crossover behavior) were flexible enough to be able to be used to accommodate the majority of transfer task conditions. Future work in this area may be better spent toward identifying body specific aspects related to self-selected stepping behaviors, as opposed to focusing on task conditions, as done by this study. Common attributes of the four flexible behaviors observed here might be an ideal starting point for such future work.
Regression models for each of the step variables within each of the behavior groups were developed. In the case of the contralateral lead foot behavior groups (one-step and two-step), separate models were developed for each transfer type and handedness condition. A total of 155 regression models in all have been presented. However, nearly one-third (47) of those models did not include any significant task or subject effects. In those situations, only the intercept (equivalent to the average value from the data for that step variable) was used. When the two most frequently observed behaviors (the one-step and two-step behaviors with the contralateral lead foot) are considered, the variables used for predicting the pickup transfer steps were more affected by the task characteristics than the associated delivery transfers step variables. Of the 126 total regression models computed for the one-step and two-step behaviors, 42 did not include any significant task or subject effects of which 34 were step variables associated with delivery transfers. One potential reason for this discrepancy may be attributed to the laboratory experiment conditions. In particular, turn angle at the delivery location was not explicitly controlled, but it was for the pickup transfers, and thus it did not vary over as large of a range. The remaining task conditions were equivalent. Another possibility is that the step requirements for the delivery transfers are not as constrained as the equivalent pickup transfers, and thus the variation in the step placements at the delivery location may be due more to within subject variations than the varied task conditions. In some cases, the RMSE (e.g. \( X_2 \) for the ipsilateral handed transfers for the one-step, \( S_I O_C C_{\text{IP}} S_I \), stepping behavior) is even smaller for the delivery predictions with no included effects, than for the associated pickup predictions. This suggests that the variance for that step variable is small in the data, and is predicted just as well, if not better, than the pickup step variable with the significant task or subject effects included in the model.

The fore-aft position of the step prior to the lead foot (\( Y_1 \) in all the split stance behaviors) has the largest RMSE values for any other positional step variable, with the exception of the one handed delivery transfers using the two step, \( S_I O_C C_{\text{IP}} O_{PC} S_C \), behavior. In those two models (contralateral and ipsilateral), manipulation height was significant, with higher delivery heights associated with smaller \( Y_1 \) (step length) values between the terminal stance lead foot and the previous step. However, even in those two cases, the \( Y_1 \)
dimension was still not predicted well. The inability to reliably predict the step length prior to the lead foot, considering that all the other step length measures are considerably better predicted, suggests that other intervening factors, not directly related to the task, are influencing that step placement. A step scaling strategy in which the step length prior to the lead foot placement is adjusted to facilitate a desired lead foot location is exploited in Chapter 5 to integrate the two separate step prediction models.

Foot orientation varied considerably between subjects and task conditions. The orientation of the lead foot (and both feet for the even stance behavior) was not well predicted with RMSE values upward of 15 degrees. One potential explanation may be attributed to the between subject variance associated with nominal foot orientations. Macellari et al. (1999) reported a standard deviations for mean foot angles observed during straight line walking for males was 4.5°. Unlike the other step variables, foot orientation was not normalized to any anthropometric body dimension in the data. Body Mass Index is a significant predictor for many of the foot orientation predicted. This may be due to the limited number of body dimensions included as potential regressors. BMI may be entering as significant effect primarily as a surrogate for a subject identifier. Foot orientations would be better interpreted, and modeled, if those values did not include a substantial amount of variation due to the between subject variability. One potential method to improve the predictions may be to normalize the foot angle predictions to the orientation of the foot observed during straight line walking. That way, the bias associated to each subject’s “resting foot angle” would be reduced.

Although the current model represents a substantial advance in the prediction of task-oriented foot motions, the application of the current model is limited in several ways. The transition behaviors presented here are from a laboratory study with a small sample size and a population of young fit participants. The limited range of participants with varied body dimensions may be one reason as to the consistency in performance across subjects, and the limited effect body size had (after scaling by stature and body mass) on the step variables. Participants also were required to wear motion capture equipment throughout the laboratory experiment, potentially constraining the self-selected movements. This may be another contributing factor as to why a small number of behavior groups account for the majority of stepping strategies observed. Each of the
transfer objects had handles (two-handed) or rubber hand rests (one-handed) to promote good coupling. The hand-object interface may significantly affect the self-selected stepping strategies used by the participants. Baril-Gingras et al. (1995) observed that operators performing MMH tasks with objects other than boxes performed significant pre and post placement phases, in addition to the transfer. Such additional requirements on the task may significantly affect how one selects a stepping strategy, in addition to how it is scaled. The laboratory environment also only contained the pickup and delivery towers as obstacles. Similar simple obstacle conditions may not exist in industrial settings, and may affect the applicability of the results.
4.8. References


CHAPTER 5

AN INTEGRATED STEPPING MODEL: A UNIFIED APPROACH TO PREDICTION OF GAIT AND ACYCLIC STEPPING FOR MANUAL MATERIALS HANDLING TASKS

5.1. Abstract

In industrial work-cell tasks, like those observed in Chapter 2, as well as in the laboratory study described in Chapter 3, transition stepping behaviors are often connected by one or more gait strides. Meaningful applications of the Transition Stepping (TRANSIT) model for digital human modeling simulations requires that those predictions be seamlessly integrated with a model of cyclic gait. Limitations for models (i.e. pushing a cart, climbing stairs, etc.) similarly integrated with gait have analogous constraints. A general approach for integrating foot placement predictions from such component models is proposed in this chapter. Foot placements are parameterized using variables similar to those utilized in Q-TRACS (Chapter 3). Steps are qualitatively defined using similar nomenclature developed in L-TRACS (Chapter 2). The general approach is implemented using a cyclic step prediction model derived from literature values and the TRANSIT model presented in Chapter 4.

5.2. Introduction

The preceding chapters have presented the development of a system for classifying stepping behavior (L-TRACS), a new quantitative parameterization of step placements during materials handling transitions (Q-TRACS), a large-scale laboratory experiment to examine stepping behavior, and a Transition Stepping (TRANSIT) model that predicts behavior selection and scaling for the three or four steps associated with an object pickup or delivery task. In real work-cell tasks, as well as in the laboratory study
described in Chapter 3, transition behaviors are often connected by one or more gait strides. Consequently, application of the TRANSIT model for digital human modeling simulations requires that the TRANSIT model be integrated with a model of unconstrained cyclic gait. Moreover, the results of Chapter 3 and 4 suggest that both the selection of the transition behavior and the scaling of the initial and final steps of the behavior depend on where in the normal gait cycle the worker is when approaching the pickup or delivery target. Hence, an accurate prediction of transition stepping depends on the prediction of the preceding and succeeding activities.

Figure 5.1 depicts the structure of the Integrated Stepping Model (ISM) developed in this chapter. The ISM requires as input a well-defined task representation, consisting of a sequence of materials handling effects defined by locations and object types. The operator is described by gender, stature, and body weight. From this input information, the ISM predicts the positions, orientations, and timing of the foot placements for the task. Following the information flow in Figure 5.1, the ISM iterates through the following steps for each MMH action in the task representation: 1) defines or accepts as input a desired path the operator should follow, 2) checks the consistency between the prescribed action and the path, 3) selects an appropriate positional step prediction model as defined by the action description, 4) simulates the foot placements and step types for that action, and 5) increments to the next action in the task representation. Once the step positions for all the actions are predicted, the combined step sequence (initially ordered temporally, based on the first initial contact of each step) is further analyzed using a deterministic decision model to predict the appropriate sequence of foot events (i.e. heel and toe contact and lifts) needed to accommodate the step progressions. The individual times associated with each foot event are then assigned using a combined empirical and physics-based approach.
Output similar to that proposed by the ISM has been suggested (and in some cases implemented) for use with controlling and predicting whole body motions. In particular, foot placements in the ground plane have been utilized as constraints to help simulate realistic motion for whole body kinematic models (Badler et al., 2005; Raschke et al., 2005; Reed et al., 2006). Forward dynamics whole body computer models have also been used with similar ground contact targets to control bipedal robots performing a variety of ambulatory tasks (Huang et al., 2001; Kajita et al., 2001; Kajita et al., 2003; Harada et al., 2005; Nakaoka et al., 2005). The current work was conceived as a modular
component of the HUMOSIM Framework (Reed et al., 2006) and is intended to be used in that context, although the ISM could be used in any human modeling paradigm. Additionally, the ISM could be used with and/or without an associated human model to perform other types of analysis. For example, the ISM could be used to conduct a planar analysis of a work-cell environment to assess the congestion of multiple operators working in the same area. In a similar context, the ISM could be used to assess the timing component of operators in a work cell environment to predict more realistic job cycle times.

The study presented here investigates the requirements necessary to implement a robust integrated stepping model. Formal definitions of a step (quantitative and qualitative parameterizations), the path the steps are modeled to follow, the individual step model outputs, and the necessary requirements to enable seamless transitions between different step types (and step models) are developed. The ISM is demonstrated using a gait model developed from the literature and the TRANSIT model presented in Chapter 4. The ISM model predictions are evaluated against a subset of the data from the experiment presented in Chapter 3 that was not used in the fitting of the TRANSIT parameters. The implications of this work are discussed in relation to whole-body motion simulation, the future development and integration of novel stepping models, and the direct and indirect impact on current and future ergonomic assessment tools.

5.3. Outline of the Integrated Stepping Model

The Integrated Stepping Model (ISM) is intended to support ergonomic analyses of work activities by ambulatory workers. More specifically, the ISM is intended to predict the foot placements and timing in the ground plane of an experienced operator performing a sequence of actions, where an action is abstractly defined here as an operation requiring whole-body movement by an operator, potentially involving an interaction between the operator and the environment, to accomplish a goal. For example, a task in a work cell environment that requires an operator to retrieve a part from a central location may involve 3 actions consisting of: (1), a walking action to the part location, (2), a lifting/pickup transfer action to retrieve the part, and (3), a carry action to bring the part (and operator) back to the original workstation. A fourth turning action may be necessary prior to the three previously described actions if the operator
was initially oriented in such a way as to require a change in orientation while walking toward the parts bin.

The definition and description of a task are closely related to the instructions an actual operator might receive to describe the necessary actions to perform a job. Predictive motion models for human figures used for ergonomic analysis may best be utilized if the users of such models are able to direct them utilizing a “high-level” vocabulary (Badler et al., 1993; Badler et al., 2005; Reed et al. 2006). For example, Badler et al. (1993) suggests “action words/verbs” such as carry, pickup, deliver, and/or walk, can be used to describe a manual material handling type task involving several part retrievals and placements. A similar vocabulary is utilized here as input to the ISM model. It should be noted that the verbs used are specifically related to individual step placement action models (described later) within the ISM, and incorporating additional descriptors may require the development of additional action models. The example implementation of the ISM includes action models used to predict pickup transfers, delivery transfers, and gait initiation, gait termination, and cyclical walk actions. Similar verbs are used in the simulation systems of major commercial human modeling software systems such as Jack (Raschke et al., 2005)

Integrated Stepping Model Inputs

The input to the ISM can be partitioned into three categories: operator, task, and specific event descriptors. Operator descriptors are comprised of a limited number of anthropometric and individual specific variables readily available in current ergonomic predictive and analyses tools. Foot length is also included to facilitate realistic visualization of the stepping patterns with respect to a particular operator, although foot length could be estimated from stature and gender. The task description is a sequence of actions in the order of occurrence, taken from a predefined vocabulary (see above). The action descriptors are the information required to sufficiently describe each action in the task description, which varies with the type of action. From the part retrieval example described above, a pickup transfer action requires as input the location of the part to be lifted, the weight of the object, and the type of object (for the current example a cylinder that can be handled with one hand or a box requiring two hands). Different descriptors
would be needed for manipulation requiring a tool, for example, but the operation of the ISM would remain the same.

Figure 5.2 depicts a MMH transfer task observed in the study presented in Chapter 2, similar in action sequence to the part retrieval example, and defines the necessary inputs for this task to be simulated using the ISM.

### Operator Characteristics:
- Age: 43
- Gender: Male
- Stature: 1.8 m
- BMI: 25.9 kg/m^2

### Task Sequence:
1. cyclical walking
2. pickup transfer
3. cyclical walking w/ carry

### Event 1: Cyclical Walking
- Curvilinear Approach Path

### Event 2: Pickup Transfer
- Pickup Location
- Approach Angle: -160°
- Departure Angle: 90°
- Pickup Height: 0.5m
- Load mass: 2.23 kg
- Lifting Hand(s): Both

### Event 3: Cyclical Walking w/Carry
- Curvilinear Departure Path
- Load Mass: 2.23 kg
- Carry Hand(s): Left

Figure 5.2. Example inputs to the Integrated Stepping Model for an existing parts retrieval manual material handling transfer task. Arrows indicate general path or trajectory of body.
Psuedo-Path Definition

In the context of ambulatory motion and particularly digital human figure models, paths are commonly used to describe and define the current and future states of a walking manikin. For example, the path of the pelvis (or one point on that segment) moving through space with each step has been used frequently to describe nominal and pathological gait (see Inman, 1981, for example). Current digital human modeling tools such as Jack™ and SafeWork™ use this approach as the primary mode for simulating walking. However, for realistic motion simulation, arbitrarily defining such a path that is directly related to a particular kinematic measure (i.e. pelvis motion) may inadvertently constrain the motion of the figure and result in implausible motion predictions. This relationship makes incorporating a path that is to be used as the input for a human figure prediction model complex, because the model should follow the path, but perhaps not too closely. In the ISM, the output of foot placements and respective timing predictions may be subsequently used as inputs and/or kinematic constraints for motion prediction simulations, and indeed for the prediction of subsequent steps. Consequently, the path, as defined here, does not directly constrain the trajectory of any body segment, but rather represents a spatial guide to different action sequences. In its simplest form, the path can be automatically generated as straight lines connecting a series of spatial locations defining materials handling tasks of interest, with the details worked out by the ISM algorithms. Paths used as input to the ISM for predicting foot placement and timing events are defined using the following criteria:

- A path is a continuous trajectory, constrained to the ground plane, that defines approximately the desired trajectory of the pelvis during bipedal ambulation, assuming a symmetric gait, and ignoring any mediolateral displacement due to the loading/unloading requirement at each step.
- A path is bounded by ‘points of interest’ (POI) that signify instances where non-cyclic steps (i.e. gait initiation, gait termination, etc.) may be encountered. It should be noted that segments of the path close to ‘points of interest’ might significantly deviate from the actual trajectory of the pelvis during whole body
motion simulations. ‘Points of interest’ may also occur along a path, for example when a sharp change in direction is required.

In the path representation presented here, the ‘points of interest’ that bound a path are manually defined by the ISM task conditions, while the ‘points of interest’ along the path may also be automatically assigned from the characteristics of the path. In the simplest form, a straight line connecting two points can be used to define a path. The ‘points of interest’ are divided into the following categories briefly described here:

- **Start Point**, a location defining the origin of the path. For the current implementation, *start point* defines a stationary, parallel stance, centered on the path, pointing in the direction of the path. In the ISM implementation presented here, the first action following the *start point* is *gait initiation*.

- **End Point**, a location defining the termination of the path. For the current implementation, *end point* defines a stationary, parallel stance, centered on the path, pointing along the previous direction of progression. In the ISM implementation presented here, the action directly preceding the *end point* is *gait termination*. Note that any number of actions can occur between a start point and end point, and actions can be defined in a loop such that no end point is necessary.

- **Turn Point**, the intended location of a significant change (to be defined later) in either:
  - the direction of progression during cyclic walking,
  - the current stationary standing stance (i.e. similar to that defined at the start point) and the subsequent direction of progression,
  - the direction of progression and the subsequent stationary standing stance (i.e. similar to that defined at the end point),
  - two stationary standing stances (i.e. potentially described as a change in stance orientation or by turning in place)

- **Pickup or Delivery Transfer**, a manual material handling object manipulation characterized by an approach, manipulation, and departure. A *transfer* is usually
associated with a transition to and from cyclic walking with the intermediate steps occurring near the time the object is manipulated.

Points of interests associated with turn points may potentially be computed automatically from path characteristics (Figure 5.3). Defining discrete turn points from curved-path characteristics is supported Orendurff et al. (2006), who presented an experiment in which experiment participants were instructed to walk along a variety of circular paths. For curved paths with a small radius of curvature, cyclical walking transitioned into a series of discrete stepping tasks for which a purely cyclical walking model was no longer appropriate. As such, the definition of such turning points of interest may be identified along a path at point $p$ if:

1. The radius of curvature $\rho$ at point $p$ is less than some defined radius $\rho_{\text{min}}$
2. Point $p$ is a point of inflection on the path (i.e. the point of maximum curvature)

Although the simplest path form is primarily used here, a path can be represented in implementation as a more complex software object with the following minimum set of attributes:

- \textit{start point}, the POI at the beginning of the path
- \textit{end point}, the POI terminating the path
- \textit{total length}, the length of the path. This length is the distance traveled while traversing the path. In the simplest path form (i.e. straight line), the total path is equivalent to the Euclidean distance from the \textit{start point} to the \textit{end point}.
- \textit{point on path (D)}, returns the point on the path a distance $D$ from the \textit{start point}.
- \textit{gradient (D)}, returns the gradient of the path at \textit{point on path (D)}.
- \textit{percentage of point on path (p)}, returns the percentage of total length that the point $p$ is along the path, measured from the \textit{start point}.
Integrated Stepping Model Output

The output of the ISM describes qualitatively (i.e., in terms of behaviors) and quantitatively (in spatial coordinates) the foot placements used during cyclical and acyclical stepping motions. The qualitative descriptions associated with the ISM output describe each type using the Lexical Transition Classification System (L-TRACS) nomenclature, presented in Chapter 2. In L-TRACS, a ‘step’ is defined as a progression of at most four foot events (i.e. heel contact, toe contact, heel lift, and toe lift), see Chapter 3 for a more detailed definition of a step. The Quantitative Transition Classification System, Q-TRACS, introduced in Chapter 3 is utilized for the TRANSIT portion of the ISM calculations. However, the ISM output presents all steps in a global coordinate system.

In the ISM output, each step is defined using nine parameters comprising the step vector $F$. Vector $F$ is given by:

$$F = [ D, f, T_x, T_y, \theta, t_{hc}, t_{hl}, t_{tc}, t_{tl} ]$$

where $D$ is the qualitative step description, $f$ is the foot (right or left); $T_x, T_y$ is the location of the foot origin, $\theta$ is the orientation of the foot (Figure 5.4), and the $t_{\text{tn}}$ are the
times of the heel contact, toe contact, heel lift, and toe lift events. The origin of the foot is defined by the projection onto the ground of the mid point between the lateral most protrusion of the fifth metatarsal head and the medial most protrusion of the first metatarsal head (see Figure 5.4).

Movement is represented as a sequence of steps defined by a step matrix

\[ S = [F_1, F_2, \ldots, F_n]^T \]

where \( n \) is the number of steps in the movement. \( S \) can be partitioned into right and left-foot components,

\[ S = [S_R, S_L] \]

The sequence of \( F \) in \( S_n \) is temporal, such that all \( t_i \) in \( F_j \) are strictly less than any \( t_i \) in \( F_{j+1} \). For example, straight line walking with a step length of 0.66 m, a step width of 0.1 m, a toe angle of 8°, and a cycle time of 1.045 seconds defined along the +y direction is depicted in Table 5.1.

![Figure 5.4. Definition of foot origin and orientation used to parameterize the placement of the foot in the Integrated Stepping Model.](image-url)

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Table 5.1. Quantitative parameterization (Q-TRACS representation) of four straight-line walking steps ($F$ vectors). Step width is set to 0.1 m, stride length is defined as 1.32 m, foot orientation is set at 8 degrees, and the direction of progression is coincident with the global +y vector.

<table>
<thead>
<tr>
<th>$F_n$ step description</th>
<th>$f$ (left/right)</th>
<th>$T_X$ (m)</th>
<th>$T_Y$ (m)</th>
<th>$\theta$ (degrees)</th>
<th>$t_{hc}$ heel contact time (s)</th>
<th>$t_{tc}$ toe contact time (s)</th>
<th>$t_{hl}$ heel lift time (s)</th>
<th>$t_{tl}$ toe lift time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$ progression left</td>
<td>-0.05</td>
<td>0</td>
<td>-8</td>
<td>0</td>
<td>0.125</td>
<td>0.334</td>
<td>0.606</td>
<td></td>
</tr>
<tr>
<td>$F_2$ progression right</td>
<td>0.05</td>
<td>0.66</td>
<td>8</td>
<td>0.523</td>
<td>0.543</td>
<td>0.857</td>
<td>1.129</td>
<td></td>
</tr>
<tr>
<td>$F_3$ progression left</td>
<td>-0.05</td>
<td>1.32</td>
<td>-8</td>
<td>1.045</td>
<td>1.17</td>
<td>1.379</td>
<td>1.651</td>
<td></td>
</tr>
<tr>
<td>$F_4$ progression right</td>
<td>0.05</td>
<td>1.98</td>
<td>8</td>
<td>1.567</td>
<td>1.588</td>
<td>1.902</td>
<td>2.174</td>
<td></td>
</tr>
</tbody>
</table>

The experiment presented in Chapter 3 can be used as a succinct example to graphically depict the positional output of the ISM (Figure 5.5). The laboratory experimental setup was intended to simulate a work cell environment in which a manual material handling transfer task was to be performed. Participants were asked to start at a particular location (depicted by the green circle in Figure 5.5), lift a load at the pickup location (depicted by one of the blue circles), carry and deliver that load to the delivery location (depicted by the other blue circle), and then walk to the end location (depicted by the red circle). The global path in this example is comprised of three straight-line paths connecting the start, pickup location, delivery location, and end ‘points of interest.’ The dark gray footprints on either side of the start location depict the initial parallel stance of the participant prior to the beginning of the trial. The intervening footprints are an example of the type of foot placement predictions that would result from the ISM. An example grouping of the predicted foot placements with the respective component models used to generate those steps is also listed.
5.4. Parameterization of a Cyclical Walking Model

The ISM integrates the TRANSIT model, presented in Chapter 4, with a cyclical walking model presented here. Cyclical walking has been studied extensively, so the cyclical walking model could be developed more expeditiously and more accurately from the literature, rather than from the data from the current study. Many independent experiments have attempted to quantify a variety of relevant walking parameters (see Whittle, 2002 for a summary) as for self-selected, or nominal, gait. For example, Perry (1992) summarizes the kinematics and kinetics, of individual body segments and joints over one gait cycle during straight line walking.
Nonetheless, the level of sophistication with which nominal gait has been reported (and simulated) in the literature varies significantly depending upon the intended application of the research. No single paper reviewed yielded the desired predictions of step length, step width, and foot orientation with the desired scope of application (e.g., both genders, a wide range of body size, self-selected speed). As such, three independent gait studies are used to construct a functional nominal stepping model that satisfies the constraints imposed by the ISM structure. Macellari et al. (1999) collected data from 596 healthy subjects and applied a multiple linear regression method (MLRM) to the dependent measures of step length (% of stride length), stride breath (% of stride length), walking cycle, swing phase (% of walking cycle), double support phase (% walking cycle), contact area, and foot orientation (referred to as toe-out angle). Potential independent variables for each MLRM model included stature, body mass, leg length, foot length, age, stride length, and walking velocity. Additionally, walking cycle, contact area, and foot angle were allowed as potential regressors for all models excluding the ones in which they were the predicted dependent measure. Samson et al. (2001) collected data from 118 women and 121 men and generated regression models for the dependent measures of speed, stride length, and cadence. Age, stature, and body weight were evaluated as potential regressors. Independent models were assessed for the male and female subjects in both those studies. Zverev (2006) collected data from 112 males and 93 females in an attempt to assess whether footedness, as defined by the Waterloo Footedness Questionnaire (Elias et al., 1998), affected step length, stride length, foot orientation (referred to as gait angle), and step width (referred to as base of gait). Additionally, summary statistics were reported for each of the dependent measures, as was also the case for the other two studies. The summary values were used here not only in comparing the results between the three studies for conceptual validation, but also for developing the functional gait model (to be implemented in the ISM), particularly for defining foot orientation, which was not well predicted by any of the models reviewed.

The age range of the participants used by Macellari et al. (1999) and Samson et al. (2001), ranging from 20 to 60 years (dataset III) and from 20 to 90 years, respectively, sufficiently spans the population of interest intended for the ISM (as presented here). Unfortunately, one potential limitation with using the three reviewed studies for
developing a nominal gait model to be used with the ISM was that in each study, the participants performed the experiment barefoot, whereas the intended application of the ISM is for workers wearing shoes.

The equations used to predict nominal straight-line gait are presented in Table 5.2. Independent models are developed for men and women for each measure of interest. Stride length is predicted using the multiple linear regression equations presented in Samson et al. (2001). Stride width (as a percentage of stride length) is predicted using the regression equations presented in Macellari et al. (1999) for the 20 to 60 year age data. The stride width regression parameters used here are the average of the low and high model parameters, which were used to assess the asymmetry between the left and right steps. A symmetric gait is assumed here and as a result, the high and low model parameter values are combined so as not to overestimate or underestimate, respectively, the average step width. Foot orientation was not well predicted in any of the studies reviewed. Macellari et al. (1999) reported a residual standard deviation (as a percentage of the mean) value of the multiple linear regression fit model for the foot orientation of the female data of 53.8%, suggesting that foot orientation is not well predicted by the selected regressors. This also suggests that predicting foot orientation by the measured mean of the male and female data sets (shown to be statistically different (p < 0.001) in the data presented by Zverev (2006)), which is the method used here, may be most appropriate considering the available anthropometric regressors. The mean foot orientation values for the male and female data sets reported by Macellari et al. (1999) are used here.

The different parameterization used to predict step width from the literature models and that used in the Integrated Stepping Model result in a slight discrepancy between the two implementations. More specifically, a significant difference in measured step width is caused when different reference points are used to measure the respective gait parameter. The selected literature models use a point on the heel to define the step width, however the ISM uses a point in the forefoot as the origin. The primary reason being that pivot steps, as observed in Chapter 2 and Chapter 3, reoriented about a point under the ball of the foot as opposed to the heel. Figure 5.6 graphically depicts the relationship between the ISM and the literature parameterizations. The predicted step
width (SW_{\text{heel}}) is scaled from the heel reference points into an equivalent step width (SW_{\text{toe}}) by the simple relation

\[ SW_{\text{toe}} = SW_{\text{heel}} + [2 \times \text{PFL} \times \sin(FO)], \]

where SW_{\text{toe}} is the step width as defined by the ISM parameterization, SW_{\text{heel}} is the step width predicted from the literature models using a point on heel as reference, PFL is the proportional foot length defined as the distance between the ISM and literature foot reference points, and FO is the foot orientation as measured with respect to the direction of progression. PFL is approximated as 2/3 of the foot length. Stride length is not affected by the different parameterizations because stride length is defined as the distance between consecutive foot placements of the same foot.

Table 5.2. Straight-line gait predictive equations and sources implemented in the Integrated Stepping Model.

<table>
<thead>
<tr>
<th>Gait Parameter</th>
<th>Predictive Equation</th>
<th>Measured Reference*</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride Length (m)</td>
<td>Male: 0.363 + -0.002 * Age (years) + 0.705 * Stature (m)</td>
<td>Female: -0.129 + -0.001 * Age (years) + -0.002 * Body Mass (kg) + 1.058 * Stature (m) +</td>
<td>Distance between a point on the heel, projected onto the direction of progression, of consecutive steps taken with the same foot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Width (% stride length)</td>
<td>24.65 + -0.0012 * Stride Length (m)</td>
<td>16.2 + -0.0335 * Age (years) + 0.078 * Body Mass (kg) + -0.00109 * Stride Length (m)</td>
<td>Distance between a point on the heel, projected onto a line perpendicular to the direction of progression, of consecutive steps</td>
</tr>
<tr>
<td>Foot orientation (degrees)</td>
<td>12.05 degrees</td>
<td>9.1 degrees</td>
<td>Included angle between the direction of progression vector and the foot vector defined by vector aligned with the longitudinal axis of the foot</td>
</tr>
</tbody>
</table>

*See Figure 5.6 for a graphical depiction of these measured references.
5.5. Integrating Predictions from Independent Component Stepping Models

The benefits of addressing a complex prediction problem with a set of coupled but largely independent component models, include the partitioning of a complex task into smaller, more manageable problems. Other benefits include a modeling structure that mimics the human conception of the process to be simulated and the potential to readily expand the simulation model by adding modular components. However, to realize these benefits, the interconnections between the components must be relatively simple, involving only a small subset of the internal variables on which each component operates.

For the ISM, it is intuitively apparent that the connections between the TRANSIT and cyclic gait components involve the steps on either side of the transition, as the worker moves into and out of cyclic gait. Among the variables manipulated by the TRANSIT model, some are predicted more accurately than others and some (mostly the same) are more important for the primary purpose of ergonomic analysis. The purpose of this section is to define and structure the meaning of principal variables associated with each component model (those that are most critical to the proper functioning of the component) and apply that definition to solving the problem of integrating disparate component model predictions.

The variables determining the lead foot placement with respect to the load are principal variables in the TRANSIT model. In contrast, the initial and final foot
placements are considered non-principal, and hence eligible for adjustment to facilitate integration of predictions from an adjacent series of steps generated from the cyclic walking model or from the TRANSIT model itself operating on a different action target. When scaling foot placements to accommodate two different component models to maintain appropriately realistic stepping patterns, principal variable values can be treated in a similar fashion as the hand positions from the associated lifting example, i.e., as fixed inputs. The non-principal variables can be permitted to vary, subject to constraints such as maximum and or minimum values for step length, step width, and/or changes in the orientation of the foot between subsequent steps.

The predictions from adjacent components can be integrated in a number of ways. One potentially appealing method is to predict all the foot placements for each event, then attempt to integrate each beginning and end foot placement of each model through continuously scaling one or multiple foot placements subject to a predetermined minimum or maximum step length (and/or width) criteria. This method assumes that the step predictions at each event are independent of the predictions defined by the previous event, but the observations in Chapter 4 show this to not always be accurate. It also assumes that modifying a predicted foot placement from one model to accommodate a smooth transition between model predictions does not significantly affect the key aspects (i.e. principal variables) of the results from either model.

Another integration approach is to, for each event in the task representation, scale the previous event model output (if necessary) to accommodate the current step predictions. This approach has the benefit of allowing the previous model predictions to be incorporated and affect (as desired) the current model predictions. If the principal variables are identified in the output of each model, steps that can be scaled by subsequent models are defined, which addresses the concern raised with respect to the previous approach in which key aspects of the previous prediction model output are not altered. This approach also is appealing in that the prediction of transitions takes place in roughly chronological order, with the behavior at one transition point determined in part by the preceding behaviors. This approach is explored in further detail in the following.

Critical to any method of merging predictions from the cyclical walking and TRANSIT models are the step scaling or adjustment strategies. Three different step-
scaling strategies, with distinctly different implications toward the modeling structure, are proposed:

1. Universal step scaling (Figure 5.6.A), in which all predicted cyclical gait steps in a sequence are equivalently scaled to a fraction of the nominal step length such that the final step, which is required to be aligned with the predicted lead foot placement (principal variable of the TRANSIT model), has the same step length as all the other predicted steps.

2. Finite step scaling (Figure 5.6.B), in which a similar strategy of step scaling is used as explained above in incremental scaling (1), except that a maximum number of $N$ steps preceding the transition are scaled.

3. Flexible step scaling, in which a hybrid strategy combining the aspects of fixed step scaling with that of the flexibility to change the lead foot behavior is utilized.

![Diagram](image)

Figure 5.7. Two simplified step-scaling strategies depicting A) incremental step scaling and B) fixed step scaling, which could be implemented to integrate a cyclical gait stepping model and a lifting step prediction model.

Variations on the universal and finite scaling approaches are possible. For example, Figure 5.6.B evenly distributes the complete distance ($B$) to travel over six steps. However, a varied distribution may be more appropriate in which the allowable difference in step length between a nominal gait stride increases as the number of steps to reach the target decreases. Another potential variation for the fixed step scaling strategy may be to define the number of scalable steps $N$ by the minimum number of steps necessary to successfully align the final foot placement subject to the constraint that each step must have a minimum step length $P$ as a percentage of the defined nominal step
length. Regardless of the variation, both the fixed and incremental scaling techniques affect only the previous event model predictions (i.e. the cyclical gait model) and not the subsequent lifting step prediction. However, in a review of a subset of the data presented in Chapter 3 in which delivery distance was varied (see Figure 5.8 for a representative set of trials), it is apparent that the lead foot selected is dependent upon the amount of change in step length that would be required to use either foot. That is, participants preferred to use a contralateral-foot-forward stance when picking up a load, but would use the ipsilateral-foot-forward stance if the amount of step scaling required to obtain the desired forward foot position was excessive. Note that this argues against both the universal scaling and finite scaling approaches, because under those approaches the participants would be expected to use the contralateral stance on all trials. More generally, these observations suggest that a useful modeling approach should incorporate knowledge regarding the foot placements for prior events in selecting the behavior (in L-TRACS terms). As such, the component model integration technique implemented here relies not on a separate model to transition between two distinct component models, but allows each component model to appropriately scale either the non-principal steps previously predicted as well as those steps to predicted during the current event.
Figure 5.8. Foot placements depicting the step lengths of one subject performing twelve transfer trials in which the delivery distance was varied. The data are from subject 1 (see Chapter 3) delivering the two handed medium load to the middle shelf of the delivery tower.

The step integration method described above is described in more detail for the specific component models developed below. Necessary assumptions and model specific
criteria are also documented for the literature derived gait model and the manual material handling transfer stepping model in the next sections. Although only these three component models (pickup transfer, delivery transfer, and gait) are described below, this method may be applicable to a wide variety of situations in which bipedal ambulation is utilized. The method has two parts: (1) selecting a transition behavior group based on the preceding cyclical gait sequence, and (2) scaling appropriate aspects of both the transition behavior and cyclical step(s).

**Selecting a Transition Behavior Group**

As suggested in the previous section and illustrated in Figure 5.8, previous cyclic foot placements affect the behavior selection at the transition location. Specifically, two split-stance behaviors which differ primarily in the lead foot at terminal stance (right vs. left) may be selected for the same transfer task, depending on the location of the target relative to the preceding gait cycle. Similar observations were made in the auto plant video data presented in Chapter 2. Consequently, the behavior sub-model assumes an equal preference between the ipsilateral versus the contralateral foot for the terminal stance lead foot. However, as previously mentioned, the observations from Chapter 2 suggest the potential that the preference for a contralateral lead foot behavior may be higher than that of an equivalent ipsilateral one. Unfortunately, the data collected in Chapter 2 and Chapter 3 do not provide sufficient clarity with respect to this scaling preference, and as such, any implementation without further experimentation would not be justified over the even preference between lead foot terminal stances as suggested here. If such data did exist, one potential method to incorporate this additional behavioral component within the current modeling structure would be to allow the previous two steps (or more depending upon the results observed in the data), as opposed to only one, prior to the terminal stance to be appropriately scaled, where the amount of allowable scaling is equivalent to the desired preferential percentage associated with each lead foot.

This dichotomy between potential stepping behaviors is modeled by introducing the lead foot scaling structure (LFSS). As suggested above, the LFSS is intended to integrate the previously predicted steps (from the cyclic step prediction model) with an appropriately selected and scaled transition behavior. The LFSS is the information required to determine if the most probable transition behavior group (defined by the
multinomial logistic model described in Chapter 4) is appropriate, including which of the possible terminal stance conditions of the ipsilateral lead foot (split stance), contralateral lead foot (split stance), or no lead foot (parallel stance) is appropriate. LFSS has two primary application cases. First, for the case in which the prediction of an even-stance transition behavior has the highest probability of occurrence among all the behavior groups, the remaining LFSS information regarding the split stance conditions is not required. This is due to the symmetry of the even-stance behavior, for which the previous foot placement configuration does not affect the selection of such a behavior, and the predicted terminal stance foot placements are always appropriate. However, as illustrated in Figure 5.8, the same statement cannot be made for the split stance transition behaviors. The second application case for the LFSS is how a split stance behavior group is selected as being appropriate (as defined by the previous foot placements) or not.

This justification is addressed by comparing the lead foot placement (as predicted by the spatial scaling models described in the next section) with a set of hypothetical foot placements, which are predicted assuming that no manipulation occurs and nominal walking continues along the direction of progression through the manipulation location. Figure 5.9 depicts the acceptable and unacceptable conditions for a contralateral lead foot behavior \( S_I O_C \) for two distinct previous foot placement predictions. The acceptable range depicted in Figure 5.9 ranges between 0.3 and 1.1 times the nominal step length (values were selected for clarity in the graphic and not modeled from data). If the predicted lead foot placement of the transition behavior is not contained in the scaled range defined by the same foot from the hypothetical walking predictions, that lead foot behavior is defined as unacceptable and the next most probable behavior (as defined by the multinomial logistic regression model) is analyzed in the same fashion.

Interestingly, if the range values depicted in Figure 5.9 are used for both the contralateral and ipsilateral lead foot behaviors, there could exist spatial locations such that neither split stance behavior would be appropriate (this is simply observed due to the acceptable range being less than a single nominal step length). Future development and population of the LFSS parameters should be mindful of such constraints. However, if the position of the load did fall in such a location, the TRANSIT component model would eventually select an even stance behavior (although it may not be the most preferable as
defined by the nominal logistic model) and that behavior would be appropriately scaled because of the previously mentioned symmetry attributed to the parallel stance behaviors. As previously described, the data presented in Chapter 2 and Chapter 3 is insufficient to accurately fit the LFSS parameters, namely a minimum and maximum step range over which the step prior to the lead foot is allowed to be scaled. As such, the minimum and maximum step range for both the contralateral and ipsilateral lead foot behaviors are implanted here as 0.1 and 1.1 (fraction of nominal step length), respectively, until further investigation can empirically determine more appropriate ranges.

![Graphical example of the method for defining whether a split stance transition behavior is A) acceptable, or B) unacceptable as defined by the previous foot placements.](image)

Figure 5.9. Graphical example of the method for defining whether a split stance transition behavior is A) acceptable, or B) unacceptable as defined by the previous foot placements.

**Scaling the Non-Principal Steps**

The non-principal steps are scaled to facilitate a smooth transition between the steps predicted by different component models in the ISM. Each component model
defines the non-principal steps as the foot placements (predicted by the component model) that are not critical to subsequent ergonomic analysis. In general, the first and last steps of each transition behavior group in the TRANSIT model are non-principal steps. All the predicted foot placements from the cyclic gait model are also considered as non-principal steps. An example of scaling the non-principal steps for integrating the TRANSIT component model predictions and the gait model step predictions is presented. Figure 5.10 depicts the predictions of the ISM over a range of start locations (depicted by the green foot prints). The changes in foot placement scaling and the transition behavior for the pickup transfer are also depicted. The cut lines in Figure 5.10 illustrated by the letters B’ and B” depict the transition between a contralateral and ipsilateral lead foot behavior as a function of the initial foot positions. One unique cycle resulting in the same transition behavior at the start and end of the cycle is represented by the inclusive distance spanning the letters A and D in Figure 5.10. The unrepeated transition behavior cycle is equivalent in length to one nominal gait stride, predicted for the operator in Figure 5.10 as 135 cm.
Figure 5.10. Example of the transition between lead foot terminal stances as a function of approach distance.
5.6. Step Timing

Integrating accurate and realistic timing for the predicted step positions is necessary for utilizing the ISM as input to whole-body motion simulations. The proposed algorithm assigns a time at which each of the four foot events per step occurs (heel contact, toe contact, heel lift, toe lift). The timing model uses the predicted global positions and orientations of each step, the sequence of each step as defined by initial contact, the type of each step, task relevant information associated with each step, and the same information regarding task sequence and operator profile as used in the component level model position predictions. The timing algorithm predicts the swing time (single support phase), the time during double support (both feet in contact with the ground), the contact interval time (the time between the initial foot contact and the next same foot event contact), and the lift interval (the time between the two lifting foot events of the same foot) (see Figure 5.11 for an example of how these relative times are defined with respect to the specific foot events).

The timing algorithm predictions are defined such that they are independent of the heel and toe specific contact and lifting foot events. Instead, the algorithm uses as reference the ‘initial’ and ‘final’ contacts and lifts of each step for defining such times as the duration of the single support phase. This abstraction is required due to the range of possible foot placements associated with each defined step type, which are more varied than normal gait. For example, the step positions and sequence of initial contact of the foot placements may require walking backward as opposed to forward (Figure 5.11), resulting in a different order of heel and toe foot events. One solution would be to more descriptively define each step such that the direction of progression with respect to the pelvis is defined. Unfortunately, this would need to be handled at the ISM component level at which the step type is selected, and would obviate the advantages of the generic step definitions in the TRANSIT model. The solution implemented here predicts the foot event order from heuristics including kinematic constraints (i.e. at least one foot must be in contact with the ground at all times), foot placement positions, and the sequence of steps defined by initial contact. The timing algorithm is presented with the assumption that the relative order of foot contacts and lifts is known for each step in addition to the information described above.
Figure 5.11. Graphical depiction of the parameterized foot events and associated step timing variables used to predict ‘walking’ steps.

The data used to develop the integrated timing model is derived from the same experimental trials used to develop the TRANSIT step scaling regressions presented in Chapter 4. For those laboratory transfer trials, the metrics in Table 5.3 were computed for each step (as previously defined).

Table 5.3. Timing Metrics Computed from Laboratory Data.

<table>
<thead>
<tr>
<th>Step Timing Measure</th>
<th>Description of the Computed Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Time</td>
<td>Difference between the current step first contact time and the final lift time of the previous step (same foot).</td>
</tr>
<tr>
<td>Double Stance Time</td>
<td>Difference between the previous step final lift time and the current step first contact time.</td>
</tr>
<tr>
<td>Contact Interval Time</td>
<td>Difference between the contact event times of the current step.</td>
</tr>
<tr>
<td>Lift Interval Time</td>
<td>Difference between the lift event times of the current step.</td>
</tr>
<tr>
<td>Step Cycle Time</td>
<td>Difference between the current foot first contact time and the previous step first contact time.</td>
</tr>
<tr>
<td>Swing Distance</td>
<td>Maximum Euclidean distance between the heel or toe points of the current and previous step (same foot).</td>
</tr>
</tbody>
</table>

The interquartile ranges of the absolute step times for the walking and transition behavior steps are listed in Table 5.4 and Table 5.5, respectively. The nomenclature used here is selected to facilitate meaningful time intervals when considering stepping motions beyond that of cyclic walking. However, cyclic walking steps from the data are also modeled as a benchmark for comparison to temporal gait parameters published in the literature. The measures of stance and swing (as a percent of a gait cycle) and cadence (steps per second) are explicitly discussed here. Macellari et al. (1999) reported a stance/swing phase (as a percent of the gait cycle) for nominal gait for men between the ages of 20 and 60 at 61.9/38.1. For a population of 24 men between the ages of 20 and
29, Auvinet et al. (2002) reported a similar pair of values at 62.25/37.75. In the gait analysis textbook authored by Perry (1992), the ‘gross normal distribution’ of those paired values is reported as 60/40 with an acknowledged dependence on speed and that for a “customary [walking] speed of 80 m/min” the stance/swing average values are 62/38. The median values from Table 5.4 are used from which the average stance percent is calculated as:

\[(2\times\text{Double Support Time} + \text{Swing Time}) / (2\times\text{Cycle Time})\]

The resulting stance/swing paired percents of 62/38 for the observed walking steps are comparable to the published literature values.

The median walking cadence of 1.72 (steps/sec) was slightly lower for the experimental data when compared with the published values of 1.91 (Chiu et al., 2006), 1.94 (Auvinet et al., 2002), and 2.11 (Samson et al., 2001). The participants in the laboratory study may have preferred a slower cadence (or longer step cycle time) than the participants in the other studies because the experimental task was considerably more complex than gait alone. As shown in the results presented by Chiu et al. (2006), slower walking speeds are associated with longer cycle times and smaller cadence values. These results qualitatively validate the equipment and methods used to capture the foot event timing. Additionally, the results also suggest that the population used for the experiment is reasonably similar to those used to construct the nominal gait parameters from the previously cited work.

Table 5.4. Inter-quartile ranges for the observed walking step times.

<table>
<thead>
<tr>
<th>Step Timing Variable</th>
<th>Lower Quartile</th>
<th>Median</th>
<th>Upper Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Time (s)</td>
<td>0.540</td>
<td>0.580</td>
<td>0.620</td>
</tr>
<tr>
<td>Swing Time (s)</td>
<td>0.400</td>
<td>0.440</td>
<td>0.520</td>
</tr>
<tr>
<td>Double Support Time (s)</td>
<td>0.080</td>
<td>0.140</td>
<td>0.180</td>
</tr>
<tr>
<td>Contact Interval (s)</td>
<td>0.060</td>
<td>0.120</td>
<td>0.180</td>
</tr>
<tr>
<td>Lift Interval Time (s)</td>
<td>0.100</td>
<td>0.180</td>
<td>0.260</td>
</tr>
</tbody>
</table>
Table 5.5. Inter-quartile ranges for the observed transition behavior step times. See Chapter 2 for definitions of the Move, Orient, Pivot, and Step types.

<table>
<thead>
<tr>
<th>Step Timing Variable</th>
<th>Lower Quartile</th>
<th>Median</th>
<th>Upper Quartile</th>
<th>Lower Quartile</th>
<th>Median</th>
<th>Upper Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transition Step Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing Time (s)</td>
<td>0.260</td>
<td>0.340</td>
<td>0.400</td>
<td>0.380</td>
<td>0.420</td>
<td>0.500</td>
</tr>
<tr>
<td>Double Support Time (s)</td>
<td>0.095</td>
<td>0.180</td>
<td>0.265</td>
<td>0.120</td>
<td>0.160</td>
<td>0.200</td>
</tr>
<tr>
<td>Contact Interval (s)</td>
<td>0.020</td>
<td>0.040</td>
<td>0.100</td>
<td>0.040</td>
<td>0.080</td>
<td>0.120</td>
</tr>
<tr>
<td>Lift Interval Time (s)</td>
<td>0.040</td>
<td>0.080</td>
<td>0.140</td>
<td>0.060</td>
<td>0.140</td>
<td>0.220</td>
</tr>
<tr>
<td><strong>Pivot Step</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing Time (s)</td>
<td>0.340</td>
<td>0.480</td>
<td>0.580</td>
<td>0.400</td>
<td>0.460</td>
<td>0.540</td>
</tr>
<tr>
<td>Double Support Time (s)</td>
<td>0.065</td>
<td>0.130</td>
<td>0.250</td>
<td>0.080</td>
<td>0.120</td>
<td>0.160</td>
</tr>
<tr>
<td>Contact Interval (s)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.060</td>
<td>0.120</td>
<td>0.160</td>
</tr>
<tr>
<td>Lift Interval Time (s)</td>
<td>0.060</td>
<td>0.080</td>
<td>0.140</td>
<td>0.095</td>
<td>0.180</td>
<td>0.260</td>
</tr>
</tbody>
</table>

Figure 5.12 graphically depicts the quartile ranges over one gait cycle for the selected timing parameters defined in Table 5.4. Interestingly, the contact and lift interval times are observed to have the largest inter-quartile range among the walking timing parameters. This seems counterintuitive as it was expected that those times would vary less (or equivalently) to those step times that encompass the interval times. However this is not the case. One potential explanation may be attributed to the laboratory equipment not being sensitive to accurately be able to reliably capture the toe contact time following the initial heel contact or the initial lift of the stance limb prior to the final lift. As the foot switches that were used to quantify the step times were non-linear pressure pads placed under the heel and ball of the foot, the second foot contact would not benefit from the large spike in pressure caused by the initial heel strike. The same reasoning would also apply to the inverse case of the initial lift and final lift that defines the lifting interval time.
Figure 5.12. Variability (inter-quartile range) in step timing for the observed walking steps depicted over one stride cycle. Median and quantile times are explicitly written as referenced to the previous foot event associated with the depicted step time. Right heel contact is set to a time of zero.

Several normalization methods were investigated that might “decrease the inter-subject variation” (Pierrynowski et al., 2001) of the step time measures and better predict the observed times across participants and step types. A similar method to that described by Hof (1996) in which gait time measures are scaled to dimensionless values by normalizing to a value proportional to \((L_o/g)^{1/2}\), where \(L_o\) is the leg length of the participant and \(g\) is the local acceleration due to gravity. The leg length \(L_o\) is approximated here as a fraction of stature as defined by Drillis and Contini (1966). The scaling value of \((L_o/g)^{1/2}\) is also proportional to the natural period of a simple pendulum (with length \(L_o\)) for small angle displacements. A simple pendulum assumes that all the mass of the swinging element is at the end the pendulum length (defined here as \(L_o\)). This is clearly not the case for the lower limb and such an approximation would tend to overestimate the actual period of the lower limb under similar conditions as the mass of the lower limb is actually distributed over the length \(L_o\). The period of a uniform rod suspended from one end, approximated by the equation \(2\pi\sqrt{(2L_o)/(3g)}\), is used here instead. Unfortunately, the equation approximating the pendulum period of the uniform rod is still limited by the small angle assumption previously mentioned for the simple pendulum. Lima et al. (2006) observed over a 1% error when using the simplified formula (as defined above) when approximating the actual pendulum period for a simple pendulum for initial angles over 25°. For all the observed steps in the laboratory, the approximated swing angle was greater than 40° in over half the conditions. The same
authors proposed an approximation of the form \( T_{\text{log}} = -T_o \cdot \ln(a)/(1-a) \), where \( T_o \) is the period of the pendulum as approximated by the simplified formula, \( T_{\text{log}} \) is the pendulum period approximation for large initial angle displacements, and \( a \) is equivalent to \( \cos(\text{initial angle}/2) \). The revised \( T_{\text{log}} \) approximation was shown to result in less than a 0.25% error for initial angles up to 90°. The final formula used to normalize the swing times observed in the data is:

\[
T_{\text{log}} = -2\pi \sqrt{\frac{3L_o}{2g} \left( \frac{\ln(a)}{1-a} \right)}, \quad \text{where } a = \cos\left(\frac{\theta_o}{2}\right), \quad \text{and } \theta_o \text{ is the initial angle}.
\]

The initial angle \( \theta_o \) is defined from the data as having the following relationship:

\[
\sin(\theta_o) = \frac{0.5 \times \text{Swing Distance}}{\text{Leg Length}}
\]

The normalization factor used to scale swing time by subject (fraction of stature approximating leg length) and task (initial swing angle as a function of observed swing distance) factors was slightly correlated (correlation coefficient of 0.3522) with swing time (Figure 5.13). Excluding the swing angle correction in the normalization factor decreased the correlation coefficient to 0.2097. This result suggests that swing angle and leg length significantly affect the self-selected swing time for nominal walking steps. However, the normalization factor of half the predicted pendulum period overestimated the observed swing time for walking steps in all cases. An obvious explanation is that the active components of the musculoskeletal system are not accounted for by the purely passive system approximated by the pendulum mechanism. This active aspect, particularly for situations in which a task is being performed like the one modeled here, can also be interpreted as subject specific motivation to perform the task at a faster or slower rate. Another potential limitation of the normalization factor is that the initial angle estimate assumes that the hip center of the swing limb is located (and fixed in space) directly in between the foot placements. However, this is obviously never the case as, for nominal walking, the pelvis translates along the direction of progression, which would also contribute to the overestimation of the actual swing time by the passive pendulum system. The bivariate plot between half the pendulum period and swing time suggests that on average, the former overestimates the observed swing time by slightly over a factor of two (Figure 5.13).
Figure 5.13. Bivariate plot of half the predicted lower limb pendulum period by observed step swing time.

The same scaling for swing time was applied to the transition behavior steps as well. However, a considerable number of steps revealed swing times with a ratio to the normalization factor greater than 1, which significantly skewed the distribution of those times to higher than expected values. The reason for these apparently extended swing times was attributed to the additional time necessary to manipulate the load (pickup or delivery) during that step. For example, the most common behavior group observed (one-step, $S_O C_{bb} S_I C_{bb} S_O$), commonly resulted in a terminal single limb stance during the manipulation. If the trailing leg was not in contact with the ground during the terminal stance and additional time (beyond that observed for an uninterrupted step) was added to the step to account for the manipulation, this additional time would manifest as an extended swing time. The same added time due to the manipulation is not constrained to extended swing times, but the measured double support time, contact interval time, and lift interval time as well. Unfortunately, due to the limitations of the data collection procedure, it is not possible to determine through the available metrics, which step time is (if at all) extended by the manipulation.

The timing predictions presented here are intended to be decoupled from the tasks defined as input to the ISM. The primary reason is that for tasks such as lifting or part manipulation, an infinite amount of time can be attributed to that manipulation and accounting for that variation in these predictions is unreasonable. As such, separate manipulation times, defined by the task, are incorporated at the terminal stance. Swing
times for all steps greater than 1 times the pendulum normalization factor were excluded. This criterion was selected based on the nominal walking swing times for which 99.5% of all swing times were less than 0.82 times the pendulum time (note that the average swing time for the walking was 0.553 times the pendulum time). The distributions of the swing times for each of the step types also suggest that this criterion underestimated the number of steps to which the manipulation affected the swing time assuming a normal distribution should be observed for the swing time for each step type. Nine hundred forty-two of the 6030 steps were excluded based on the swing time criteria. Interestingly, all the excluded steps occurred as the 3rd step in the transition behavior and for each of the five most frequent transition behaviors included in this data set, this corresponds to the step following the terminal stance. This result suggests that for these manipulation trials, the participant was in single limb stance during the manipulation and that extra time manifested as longer than usual swing times.

The same exclusions were performed for steps with significantly longer double support times, contact interval times, and lift interval times. Steps with a double support time, expressed as a percentage of swing time, greater than 1 were excluded. Compared to the walking steps, the average double support time (as a percentage of swing time) is 0.302. Additionally, 99.5% of all double support times were less than 0.909 times the swing time. Five hundred thirty seven step trials were excluded due to this criterion. Eighty seven percent of the excluded steps occurred second in the transition behavior. This suggests that the manipulation occurred during a terminal stance while both feet were in contact with the ground and prior to the subsequent step. Steps with contact and lift interval times greater than 0.3 and 0.5 seconds, respectively, were also excluded. For the 139 steps excluded by the contact interval time criterion, 37% were the second step in the transition behavior and 58% corresponded to the third step. For the 430 steps excluded by the lift interval time criterion, 39%, 39%, and 16% of the exclusions corresponded to the first, second, and third steps respectively. The analysis of the subset (non-excluded) transition behavior steps for the different step timing variables is presented here.

The four timing parameters of swing time_SPN (swing time scaled by the pendulum normalization factor), double support time_SWT (as a fraction of swing time),
contact interval time (seconds), and the lift interval time (seconds), were compared by step type using the Tukey-Kramer HSD test (p<0.05). For only the transition steps (i.e. see Chapter 2 for a more detailed description of the pivot, orient, move, and step descriptors) focusing only on the observed swing time, the move steps were significantly shorter than the other steps with a mean swing time_SPN of 0.50. The remaining significantly different step groups by swing time_SPN consisted of the orient step significantly different from either the step and move steps, and the step and pivot movement significantly different than the orient and move step types. The average observed swing time_SPN values for the orient, step and pivot step types were 0.55, 0.57, and 0.62 respectively. The average swing time_SPN for the walking steps was 0.55.

Double support time_SWT was significantly different for the following groups: step, pivot and orient, and move steps. The average double support times_SWT for the step, pivot, orient, and move step types was 0.27, 0.39, 0.48, and 0.56, respectively. Each step type (excluding the pivot step which does not have a contact interval time) also had a significantly different contact interval time. The lift interval time was significantly different between the step and remaining step types in addition to significantly different lift interval times for the move and orient step groups.

The contact and lift interval times are not scaled and presented here as absolute times. The primary reasoning for such a decision is that those times are not critical to the application of the ISM as described here. For example, the progression between each step, from a time analysis perspective, needs to correctly evaluate the cycle time between steps to properly estimate the necessary time to complete a particular task. Additionally, the contact and lift interval times can be considered ‘within step’ times and do not affect the initial contact or final lift times that would traditionally be used to define a step, stride, or even job cycle time. However, for the proposed application in which the ISM is used to drive the bipedal motion of a human figure model, those times are critical for realistically representing natural and plausible stepping motions. The definition of such within step times are better left up to the discretion (or definition) of the human figure model so as not to over constrain the bipedal motion simulation.

Particularly for the lift interval time, inverse kinematics methods may be better at producing realistic initial lifting motions. For example, consider the timing of the initial
lift of the support foot during or immediately following the single support phase of a simulation of nominal straight line walking. For a short step length of the swing limb, the lift of the support step may occur after the initial contact of the opposite limb. For a longer step length, the lift may be required to occur before the initial contact of the swing limb simply to satisfy the kinematic constraints of matching the swinging limb foot placement to the predicted location. However, what determines a short or long step? Clearly that question can be assessed given the stature of an operator (one input to the ISM). Yet, the question may be better answered given the anthropometry of the human figure model for which leg segment lengths are more accurately defined. Or rather, the question may not need to be answered explicitly, but could be solved using a set of constraints imposed on the motion control scheme.

The step times previously defined are predicted using a linear regression modeling approach similar to that used to model the foot placements. An automatic stepwise procedure was used to populate the model with potential regressors (p<0.001 to enter and p<0.005 to leave). Subsequently, an ad-hoc method of selecting parameters was used to obtain a more parsimonious model. Table 5.6 lists the predicted variables along the left most column and summary statistics regarding the model fit and potential regressors as the remaining columns. Different models were developed for the walking steps and the transition behavior steps. Cycle time was used as a normalization factor for determining the double support time for the walking steps as that was shown to be less variable than using swing time only. The potential regressors included subject stature, leg length (approx), subject BMI, approximated swing angle (radians), and the type of step (for the transition steps only). Only swing angle and step type were entered into the final fit models.

Only the swing/double support time (as a percent of cycle time) fit models included any regressor terms for the timing variables associated with the walking steps. The poor model performance (adjusted $R^2$) of those models suggests that none of the timing variables is strongly associated with the potential regressors. However, the similar RMSE values for each of the walking step timing models suggest that the null model for the swing time (as a % of the half pendulum period) and the contact and lift interval times varied equivalently in the observed data. The nominal variable of step type was included
in all of the transition step timing prediction models. The relatively low RMSE for the contact interval time model for the transition steps suggests that both the heel and toe contacted the ground in a consistent manner for each transition step type. Another potential explanation, supported by the inter-quartile ranges presented in Table 5.4 and Table 5.5, is that the contact interval times for the transition behavior steps did not vary over as wide of range as that observed for the walking steps.

Table 5.6. Table of walking and transition step timing prediction models*

<table>
<thead>
<tr>
<th>Step Timing Variable</th>
<th>R² (adj.)</th>
<th>RMSE</th>
<th>Intercept</th>
<th>Swing Angle (rad.)</th>
<th>Step Type (Move) #</th>
<th>Step Type (Orient) #</th>
<th>Step Type (Pivot) #</th>
<th>Step Type (Step) #</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Walking Step</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing Time (% Half Pendulum Period)</td>
<td>0.00</td>
<td>0.113</td>
<td>0.556</td>
<td>-</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Swing Time (% Step Cycle Time)</td>
<td>0.12</td>
<td>0.116</td>
<td>0.640</td>
<td>0.094</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Double Support Time (% Step Cycle Time)</td>
<td>0.12</td>
<td>0.116</td>
<td>0.360</td>
<td>-0.094</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Contact Interval (s)</td>
<td>0.00</td>
<td>0.113</td>
<td>0.136</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Lift Interval Time (s)</td>
<td>0.00</td>
<td>0.108</td>
<td>0.196</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Transition Step</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing Time (% Half Pendulum Period)</td>
<td>0.02</td>
<td>0.136</td>
<td>0.529</td>
<td>--</td>
<td>-0.100</td>
<td>0.010</td>
<td>0.050</td>
<td>0.039</td>
</tr>
<tr>
<td>Double Support Time (% Swing Time)</td>
<td>0.05</td>
<td>0.168</td>
<td>0.345</td>
<td>--</td>
<td>0.148</td>
<td>-0.017</td>
<td>-0.039</td>
<td>-0.092</td>
</tr>
<tr>
<td>Contact Interval (s)</td>
<td>0.06</td>
<td>0.066</td>
<td>0.089</td>
<td>--</td>
<td>-0.025</td>
<td>-0.004</td>
<td>NA</td>
<td>0.028</td>
</tr>
<tr>
<td>Lift Interval Time (s)</td>
<td>0.04</td>
<td>0.108</td>
<td>0.137</td>
<td>--</td>
<td>-0.044</td>
<td>0.010</td>
<td>-0.017</td>
<td>0.051</td>
</tr>
</tbody>
</table>

* Values in tables are coefficients of the associated regressor terms. The regression function is the sum of the products of the coefficients and the variable values, plus a constant intercept.
† A -- indicates that the model coefficient was not significantly different from zero.
# Step Type represents a nominal variables and only one value from this group should enter the regression equation at any one time.

As previously suggested, the timing model presented here focuses on simulating step times for uninterrupted bipedal movements. Unfortunately, one potential use of this model is as a method for more realistically estimating actual human movements around a work-cell environment. Traditionally, value-added operations (often those of interest for ergonomic simulation, such as attaching a part to an assembly) require additional time not accounted for by the model as previously presented here. However, the additional times are task specific and a separate timing model to predict those task times is beyond the scope of the work presented here.

To more clearly illustrate these issues, consider two stepping behaviors, one with a parallel terminal stance and one with a split terminal stance. For the parallel terminal
stance behavior, the task could essentially be of infinite time and not affect the selection of such a behavior and any predicted time would be inappropriate. However, for a split stance behavior, it has been observed that for tasks at which the operator underestimates the actual task time requirement, the split stance transitions into a more appropriate parallel stance for which standing for an extended period may be more reasonable. This suggests that for certain transition behaviors (including the single-foot-support behavior that represents a plurality of the laboratory data), a maximum job time is associated. In the ISM structure, this issue is handled by appropriately defining what type of task is being performed (i.e. a delivery transfer versus a delivery stay).

In application, specific task times will be associated with tasks and passed as input to the ISM. However, for the transfer tasks modeled here, the average observed manipulation times are presented for each of the transition behavior groups. The manipulation interval is defined as the difference between the initial contact time of the final step before the manipulation and the initial contact time of the subsequent step. The manipulation time is presented as the manipulation interval minus the average cycle time for that step type in the behavior. Figure 5.14 depicts the manipulation intervals and times for the five behavior groups. Interestingly, the contralateral lead foot split terminal stance behaviors were observed to have the longest manipulation intervals and times among all the behaviors. Interestingly, a small number of trials for each of the behaviors was observed to result in a manipulation time less than 0 (Figure 5.14.A). This was possible if the manipulation interval was shorter than the average cycle time for that step type. This suggests that manipulation time should not be treated as a simple additive (as is done here) to the nominal time necessary to complete the stepping motions, but is more complex and needs to be further researched with respect to whole body coordination including, but not limited to, the interactions between stepping, reaching, lifting, and grasping. The current implementation of the timing model adds the manipulation time to the appropriate timing variable that corresponds to the most frequently observed behavior within each behavior group.
5.7. Model Implementation and Performance

A working version of the Integrated Stepping Model has been implemented in the Matlab computing language. A graphical user interface (Figure PK) is used to input the necessary subject and task characteristics. The Matlab implementation is constrained to four points of interest (including two transfers) in which task actions progress in order beginning at the start location, followed by the pickup transfer location, then the delivery transfer location, and concluding with the end location. A parallel stance centered about the start and end locations are assumed for the initial and final foot placement conditions, respectively. The transfer object is modeled as a one or two-handed load with an
associated mass. The same object used at the pickup location is used at the delivery location. The hand used to manipulate the load is defined as a user input (i.e. the model does select which hand an operator uses to manipulate the load).

Figure 5.15. Graphical user interface for the Matlab implementation of the Integrated Stepping Model.

The implementation GUI is divided into three major parts, (1) top view of the task conditions and predicted foot placements (top-left in Figure 5.15), (2) task and subject input parameters (top-right in Figure 5.15), and (3) $S$-matrix (Q-TRACS) variables associated with each predicted step (bottom in Figure 5.15). On a 1.67 Ghz PowerPC running Mac OS X, the time to perform the prediction takes approximately 15 seconds.

The TRANSIT model formulation is parameterized to be independent of turn direction. The Matlab implementation calculates turn direction as the direction resulting in the minimum included angle between the straight-line paths defined between the points of interest. The implementation is hard coded to always begin the first step (following the parallel stance at the start location) with the right foot. Figure 5.16 depicts four mirrored left turn predictions similar to the right turn pickup transfer depicted in Figure 5.16.A. Figure 5.16.B is the prediction for a similar transfer task as in (A), with the delivery and end locations mirrored to represent the positions of an equivalent left turn
transfer. Figure 5.16.C is similar to Figure 5.16.B with the transfer hand also being equivalently mirrored. Figure 5.16.D is similar to Figure 5.16.B with the start location adjusted to facilitate an equivalent mirrored right foot forward split stance transfer strategy. Figure 5.16.E is the equivalent left turn transfer task to Figure 5.16.A.

Figure 5.16. Influences affecting the prediction of equivalent right and left turn transfer steps. A) Original right turn transfer task performed with the left hand and a left foot forward strategy. B) Similar to (A) with mirrored delivery and end locations. C) Similar to (B) with mirrored transfer hand condition. D) Similar to (B) with adjusted start location to replicate a right foot forward pickup transition behavior. E) Equivalent left turn transition to (A) with mirrored delivery and end locations, transfer hand, and lead foot stepping behavior.

More output from the ISM are depicted in Figure 5.17, Figure 5.18, and Figure 5.19. Step predictions for a range of start, pickup, delivery, and end locations plotted. The range of conditions explored includes and exceeds those task conditions used to populate the TRANSIT model (Chapter 3). However, plausible foot placement
predictions are shown for all conditions. Figure 5.20 depicts one such example in which the ISM results in plausible step placements for a close proximity pickup and delivery transfer. It should be stressed that such predictions are not validated and future work should focus on such efforts. However, the quality of predictions for task conditions well beyond those observed to develop the specific equations in the ISM suggests that the ISM parameterization (Q-TRACS and L-TRACS) is useful for further constraining the vast number of possible prediction combinations resulting in meaningful predictions.

Figure 5.17. Example ISM predictions from the Matlab implementation.

Figure 5.18. Example ISM predictions from the Matlab implementation.
Figure 5.19. Example ISM predictions from the Matlab implementation.

Figure 5.20. Example of predicted pickup and delivery transition foot placements for a close proximity transfer.
5.8. Discussion and Conclusions

This chapter has presented an integrated approach to predicting both cyclic and acyclic (transition) stepping in an industrial work-cell environment. The gait component of the ISM represents cyclic stepping using the same parameterization of step placement developed in Chapter 3 for quantifying foot movements and applied in Chapter 4 in the development of the TRANSIT model. In this context, gait is viewed as a special case of stepping with a single behavior, in contrast to the five behaviors modeled for transition stepping.

With this foundation in place, the ISM could be readily extended to represent other types of task-oriented stepping. In particular, one important component lacking in the current implementation is locomotion along a curved path. Although the internal representation and calculation of the step placements with respect to the curvilinear path may be different, the same generalized output comprised of foot vectors $F$ and step matrices $S$ required by the ISM will remain unchanged if a curvilinear model is implemented. Additionally, the generalized parameterization of linear walking measures to non-linear paths by Huxham et al. (2006) may potentially allow the internal representation of using step lengths and step widths to remain consistent.

Linear step prediction models can also be considered as a special case of more abstract curvilinear implementations. In his book, Badler (1993) explores curved path walking in the context of digital humans and proposes a method for generalizing a one-dimensional (linear path) locomotion algorithm into a two-dimensional one. Another approach for realizing curved path stepping predictions may also be developed from the results presented by Orendurff et al. (2006), in which the kinematics of walking along a circular path (at different radii conditions) are explored. It may be possible that stepping along a variable radius curved path may be appropriately modeled utilizing data from such independent circular path walking tasks.

One potential limitation of the step integration methodology as presented is the possibility of two or more events being close enough that the integration of steps predicted from those models should incorporate not just the previous model, as implied above, but steps predicted from previous events as well. This issue is only partially addressed with the incorporation of the principal versus non-principal step descriptions,
of which not just the previous event foot placements are available to be scaled during the current event, but the cumulative compilation of the steps taken up to that point. However, for situations in which the proximity of actions changes the defined task (which may then potentially affect the stepping strategy), a new action should be defined that better models the stepping behavior for that new task. For example, a task sequence in which a pickup and a delivery transfer are uniquely defined may become coupled as a single action with a pickup and delivery component as the two transfer locations converge. The results from an experiment presented by Delisle et al. (1999), in which experienced operators selected foot placements to facilitate similar close proximity transfers, supports these added actions. In this way, the limitation associated with integrating multiple events that are close together is handled by the redefinition of the task sequence, which occurs at a different place within the ISM.

The ISM, and its component gait and TRANSIT models, represent a substantial departure from much of the gait simulation literature, but at the same time are consonant with and support some of the leading developments in digital human model simulation for ergonomics analysis. The focus on the placement of the steps differs from most gait literature, which has generally taken step placement (stride length) as a given, and focused instead on the kinematics and the biomechanics of the limbs that result in the step placements. The repetitive nature of cyclic stepping makes the step placement problem relatively simple (compare Table 5.3 of this chapter, describing step placements for cyclic stepping in Q-TRACS with the complex transition step placement models in Chapter 4). Indeed, the development of the TRANSIT model required the development of new terminology for describing patterns of foot behavior (the L-TRACS notation) and new local methods for quantifying foot placements and the effects of task and subject variables on those foot placements.

Applications of the ISM in digital human models presume that it is feasible and meaningful to predict step placements using a relatively small set of input dimensions, and, most importantly, that concurrent simulation of what the rest of the body is doing is not required. From a practical standpoint, Badler et al. (2005) have demonstrated that kinematic simulation of locomotion is aided by the application of foot placements as intermediate variables, computed from task and environment variables and subsequently
input to whole-body simulation. More recently, Reed et al. (2006) have shown that whole-body simulations of materials handling tasks can be generated using foot placements as an input. Indeed, even researchers focused on predicting human locomotion from biomechanical principles have used foot placements as input (Chung et al., 2007).

From a motor control perspective, the steps-first prediction approach elevates the steps to a higher level of control, proposing, in essence, that people plan their foot placements and organize their other motions (for example, lower extremity kinematics) to accomplish those foot placements. This seems readily apparent in activities such as stair climbing. For other activities, such as running, the steps-first prediction approach may not be as appropriate. The results of the behavior selection and scaling observed in Chapter 3 suggest that foot placement takes place in a context that includes the selection of behaviors (step sequences) from a small repertoire. Task conditions (for example, turn angle) lead to preferences for one behavior, but an alternative behavior (ipsilateral lead foot, for example), may be selected if the person enters the area of the transition at a point in the gait cycle in which it would be awkward or infeasible to use the preferred movement pattern.

This chapter presented a heuristic approach to connecting the transition behaviors, which are assumed to be selected from a small repertoire, with the incoming cyclic strides. The LFSS solves the problem by identifying the first step in the transition behavior and the last gait step as potentially scalable to adapt the gait to the transition. However, limits on the amount of scaling mean that the algorithm can discard the preferred behavior as inappropriate (awkward, in movement terms) and instead select an alternative behavior that could be performed in a more natural manner, i.e., without excessive modifications to normal step length. This step scaling (and behavior selection) system models the laboratory data well, and also appears to capture many of the behaviors observed in the field study. Of course, a person could choose a more awkward movement pattern that deviated from these typical behaviors, but the ISM does a good job of capturing normal behavior for digital human modeling applications. Future research should focus on the continued development of additional component level step
prediction models to expand the tasks for which the ISM can be applied and a more rigorous evaluation of the integration process.
5.9. References


CHAPTER 6

SUMMARY AND FUTURE RESEARCH

6.1. Overview

The work presented in this dissertation focused on understanding and modeling the effects of task requirements on foot placements during Manual Materials Handling (MMH) transfer tasks. Four investigations were conducted to facilitate the main objective. First, a novel classification system was developed to characterize the stepping patterns used by operators in an industrial work cell performing MMH transfers. Second, the effects of MMH transfer task characteristics and subject factors on foot placements within the most frequently observed stepping pattern were investigated. Third, a multinomial logistic regression model to select a stepping pattern and several multivariate regression models to scale the steps of that pattern were evaluated and the residual model variability was compared to within and between subject variability estimates. Finally, a formulation of an integrated stepping model was proposed that incorporates the acyclic step predictions previously developed with a cyclic gait model derived from published research. The following sections outline the contributions of this research and recommend directions for future work.

Summary of Principal Empirical Findings

- Split stance transfer behaviors were ubiquitous and accounted for 92.5% of the total transfers observed in the laboratory study. The task performed in the laboratory study was for a participant to (1) approach an object on a shelf from 3-4 steps away (2) pick up an object, (3) deliver that object to another shelf 2-5 steps away, and finally (4) return to the original start location.
• Two-thirds of the object pickup and deliveries were performed with only one foot in contact with the ground.

• The majority of stepping progressions used for manual materials handling transfer tasks can be represented by a concise set of scalable stepping behaviors that are a significant subset of those observed in manual materials handling tasks.

• Transfer type, lifting hand, shelf height, and turn angle each have significant effects on step behavior selection.

• Turn angle and the hand(s) used for the task (left, right, or both) are the primary determinants of the lateral placement of the lead foot for transfers in which the “one-step” behavior \( (S_I O_C C_{BB} S_l) \) was used. A similar relationship also was observed for the remaining stepping behavior groups investigated.

• For transfers, in which the “one-step” behavior \( (S_I O_C C_{BB} S_l) \) was used, the lateral placement of the lead foot was symmetric about the approach vector for ipsilateral- and contralateral-handed transfers. The most contralateral foot placements were associated with the ipsilateral handed transfers.

• For two-handed transfers, in which the “one-step” behavior \( (S_I O_C C_{BB} S_l) \) was used, the lateral placement of the lead foot was on average contralateral to the direction of turn (e.g., an average of 2.9 cm from the approach vector for a 175 cm stature operator).

**Unexpected Findings**

• Object mass (as a fraction of body mass) was not a significant factor for predicting the fore-aft lead foot placement for the majority of stepping behaviors. Object mass had a significant effect on lead foot placement only for (1) the contralateral-handed pickup transfers involving the “one-step” \( (S_I O_C C_{BB} S_l) \) behavior, (2) the ipsilateral-handed pickup transfers involving the “two-step” \( (S_I O_C C_{BB} O_S C) \) behavior, and (3) the two-handed pickup transfers involving the “two-step” \( (S_I O_C C_{BB} O_S C) \) behavior.
Summary of Principal Contributions

- A novel classification system (L-TRACS) was developed to characterize the stepping patterns during manual materials handling transfer tasks.
- A meaningful consistency of stepping behaviors is observed within and between individuals performing well-learned and practiced jobs with an accurate knowledge of the environment, including the characteristics of the objects to be manipulated.
- A general parameterization of the foot placements for the L-TRACS stepping behaviors was developed (Q-TRACS) to mathematically represent each stepping pattern and incorporate the previous and future requirements of the task being performed.
- A Transition Stepping (TRANSIT) model was developed to predict the foot placements from laboratory data for commonly observed manual material handling transfer stepping patterns.
- A framework for integrating separate step prediction models (the Integrated Stepping Model, ISM) was proposed and implemented using the TRANSIT model and a gait model derived from previous research.

6.2. Research Context

The study and modeling of foot positions and stepping strategies during objective oriented tasks expands upon previous research from three broad categories: lifting (manual materials handling), walking and turning, and compensatory stepping.

Lifting

The effects of varied foot placements on lifting technique, whole body kinematics, and stability have been studied (Bendix et al., 1983; Delisle et al., 1996; Gagnon et al., 1993; Holbein et al., 1997; Hsiang et al., 1997; Kingma et al., 2004; Kollmitzer et al., 2002; Lavender et al., 2003; Meinhart-Shibata et al., 2005; Planmondon et al., 1995; Zhang et al., 2003). Kollmitzer et al. (2002) studied the effects of parallel and “step” (defined in the current work as “split”) stance on the complexity of required control strategy to maintain stability in both the lateral and fore-aft directions. A coordinated movement strategy in which the participants moved their pelvis forward and trunks backward simultaneously to maintain stability was observed during the parallel
stance lifts. For the step stance lifts, participants were instead observed to move their pelvis backward prior to the lift and utilize that backward momentum to facilitate the lifting of the load. However, the study only required subjects to manipulate one load (two-handed box with mass of 4.6 kg), between one set of pickup and delivery shelves located approximately 75 cm apart, with prescribed foot locations (i.e. on top of two force plates). The study did not address the question of subject preference for either lifting strategy and the conclusion as to which strategy should be recommended in terms of postural control was inconclusive.

Authier et al. (1996) investigated the effects of self-selected lifting strategy for novice and experienced manual material handlers performing two-handed pickup and delivery transfers with different configurations of object mass, lifting height, and box orientation (48 unique trials). The results suggested that the “positioning of the feet could be a significant execution parameter.” Furthermore, it was observed that the expert handlers did not select foot positions directly in front of the load, but chose foot placements (at the instance of lift) directed toward the delivery location. Unfortunately, only a single delivery direction (90° turn) was tested, limiting the applicability of the results.

Meinhart-Shibata et al. (2005) investigated the effects of age on the stepping strategies and kinematics of participants performing a pickup transfer followed by a 180° turn. The results suggest that the older population preferred a preparatory stepping strategy (defined by a pivot step being performed by the contralateral foot, with respect to the turn direction, as the first step in the strategy). However, only one turn angle, object, and lifting height combination was tested, significantly limiting the applicability of this work to simulating manual materials handling transfer tasks in industry. Although many other studies have examined lifting and materials handling in specific contexts, no general model to predict stepping behaviors across a wide range of task conditions has previously been developed.

Walking and Turning

The classification and parameterization of walking along a straight path (see Perry, 1992 for a review), along a circular path (Oredurff et al., 2006), and the turning steps used to transition between straight paths (Huxham et al., 2006) have provided
methods for comparing and predicting the step placements and timing for different tasks and populations (Grieve et al., 1966; Dahlstedt, 1978; Hase et al., 1999; Samson et al., 2001; Auvinet et al., 2002; Al-Obaidi et al., 2003; Owings et al., 2004a; Owings et al., 2004b; Hausdorff, 2005; Orendurff et al., 2006; Zverev, 2006; DeMott et al., 2007; Fuller et al., 2007). The commonly used metrics for parameterizing cyclic straight-line walking (i.e. step length, step width, cycle time, etc.) have been used to compare the symmetry in gait (Hurmuzlu et al., 1996; Auvinet et al., 2002), changes in gait associated with age (Dahlstedt, 1978; Auvinet et al., 2002; Richardson et al., 2005), and changes in gait associated with pathological disorders (Perry, 1992; Hausdorff, 2005). However, those metrics require that the gait being analyzed follow a straight-line path (i.e. direction of progression). Orendurff et al. (2006) investigated the kinematics of walking along a 1-m-radius circular path and observed that the step lengths of the outside steps were longer than the inside steps for self-selected and prescribed faster and slower walking speeds. However, only one radius for the circular path was used and other types of turns were not studied. Huxham et al. (2006) introduced a method for defining the spatial parameters of gait to better understand tasks involving “functional locomotion” in which non-linear walking (defined by a change in the direction of progression) is required. The spatial parameterization of each step is defined with respect to a previous foot location. However, for situations in which foot placements are scaled to accommodate a step location with respect to a globally defined reference (i.e. the location of an object to be lifted), the proposed parameterization is not directly applicable. The new method for qualitatively identifying and comparing unique stepping patterns developed in the current work provides a better understanding and classification of the observed stepping strategies during goal-directed stepping tasks, particularly those involving manual material handling pickup and delivery transfer tasks.

**Compensatory stepping**

Models of compensatory stepping strategies have provided insight into when a compensatory step might be utilized (Pai et al., 2000) in addition to the timing and position of such a step (Maki et al., 1999). Compensatory stepping is a functional method for maintaining balance. However, other postural adaptation strategies, namely the “hip-strategy” and “ankle-strategy” are also observed, in which balance is maintained
by pivoting about the named joint (Maki et al., 1997). When modeling such behaviors, in which the selection of the most appropriate behavioral strategy is not well defined, a two-stage modeling approach that selects, and then scales the selected behavior is necessary. In the current work, a general two-stage modeling structure similar to approaches that have been used to simulate the compensatory stepping behavior was applied to the stepping patterns used during manual material handling transfer tasks. A discrete selection process that identifies the most appropriate behavior strategy for the defined transfer task is followed by a continuous scaling process of the step variables that define each step in the behavior.

6.3. Application Context

The use of digital human models for prospective ergonomic assessment requires representative postures and motions for accurate biomechanical analysis (Chaffin et al., 1991). Small discrepancies in joint kinematics can result in large errors in internal body forces and moments (Holden et al., 1997; Reinbolt et al., 2007). Simulation is a viable and cost-effective method for defining realistic and reproducible input postures for prospective biomechanical analysis (Chaffin, 2005). However, the large number of degrees of freedom of the human linkage results in an infinite number of possible simulated postures for a given task. The overall complexity increases for simulations requiring multiple postures and/or motion. Unfortunately, the current simulation tools (i.e. posture prediction algorithms) included in commercial human modeling applications are inadequate in several ways. The tools require a considerable amount of time and manual manipulation to create postures, the resulting postures are not validated, and the repeatability and reproducibility (across operators) is poor (Wegner et al., 2007).

The current work focusing on foot placements is motivated by the critical influence of the location of the base of support on biomechanical analyses of standing tasks. Foot placements have been shown to strongly affect whole-body posture and motion, and subsequently affect the stresses on the low back and other body regions that are being analyzed (Kingma et al., 2004; Wagner et al., 2005; Plamondon et al. 2006). Unlike the hands, which are traditionally constrained to known object or part locations during simulated MMH tasks, the locations of the feet are not as well defined. No general model is known to be available at this time for predicting the location of an operator’s feet with respect to a MMH transfer task. However, the need for such a model
is highlighted by the requirement (and current limitation) identified by Wegner et al. (2007) in which current simulation algorithms used to drive DHMs must reproduce realistic walking and stepping motions while the human figure moves about the work environment. Additionally, without accurate constraints on the whole-body location of the predicted figure with respect to the task, biomechanical models using those postures to predict internal body stresses will not be representative of actual performance (Chaffin et al., 1970; Ayoub et al., 1995; Ayoub, 1998; Dysart et al., 1996; Perez, 2005).

6.4. Principal Contributions

The four research objectives presented in Chapter 1 were achieved and broadly outline the principal contributions of this work. Those objectives are repeated and further discussed.

1. **Develop a method for representing and classifying the stepping patterns frequently observed during manual material handling lifting transfer tasks, and present the frequency and distribution of transfer tasks conditions, and the associated stepping patterns within an industrial setting.** This work, presented in Chapter 2, identified the need for a rigorous cataloguing methodology to adequately capture the acyclic stepping patterns associated with MMH tasks. In developing such a method, the broader question of how to catalogue the large range of possible stepping patterns people use during work tasks was addressed. Although a complete yet concise taxonomy was developed, the main contribution associated with this work was the application of the taxonomy to the industry transfer tasks presented in Chapter 2. For the first time in the literature, stepping behaviors associated with industrial tasks have been quantified, and a small number of stepping behavior groups were demonstrated to represent the large majority of observed stepping patterns. In particular, the seven most frequently observed behavior groups accounted for over 90% of all observed stepping patterns. Related results from the application of the taxonomy on the industry work cell data include the prevalence of utilizing a split stance behavior at the terminal posture (i.e. when the load is manipulated), the predominant number of transfers being executed while standing only on one limb, and the increased prevalence of contralateral lead foot terminal postures (lead foot is on the opposite side from the turn direction) over ones utilizing the ipsilateral lead foot. These observations provide the justification and means
for appropriately selecting the stepping patterns that are most relevant for study and analysis as pertaining to experienced operators performing well-learned MMH transfer tasks.

2. **Investigate the effects of anthropometric variables and task conditions, consisting of the lifting hand(s), object height, object weight, approach angle, departure angle, and turn angle on step pattern selection and foot position(s), with respect to object location during manual material handling lifting tasks.**

Chapter 3 describes a laboratory experiment to address this objective in which participants performed MMH transfers tasks similar to those described in Chapter 2. The hypothesis that task conditions significantly affected stepping pattern selection was tested against the null hypothesis (i.e., that task demands were not significant predictors of behavior selection). The data supported the rejection of the null hypothesis as significant differences (p<0.01) for turn angle, shelf height, handedness, object mass, operator stature, and operator BMI were observed across the five selected stepping behavior groups. The remaining observations were tested on a subset of the data for which the most frequent stepping behavior group was observed for pickup transfer trials. For clarity, a right turn following the manipulation is assumed for this discussion. The hypothesis of symmetry in the lateral lead foot location between the different handedness conditions (left, right, both) was tested. The data supported the hypothesis of symmetry between the one-handed conditions with the lateral location of the lead foot being located at 0.04377*stature and -0.0437*stature (0 being the location of the object and positive pointing to the right) for the left- and right-handed conditions, respectively. However, the data did not support the hypothesis for the two-handed condition, as the lead foot was placed significantly to the right of the object location and not in line with the approach direction.

Object mass was hypothesized to significantly affect the distance between the lead foot and the object (in the ground plane) with heavier loads resulting in a shorter lead foot to object distance. The data partially supported the hypothesis with a significant difference being observed between the light and heavy loads for left handed pickups and between the medium and heavy loads for the two handed pickups (following the hypothesized trend). However, for the right-handed pickup trials, a similar result was not
observed and the trend between the light and medium loads for the two handed pickups was observed to be the opposite of what was expected with the lighter loads (on average) corresponding to a shorter distance between the lead foot and the object. Although other hypotheses were tested that pertained to specific task conditions and step variables, those tests all support the general observation that the prediction of transition steps depends on workplace geometry, subject characteristics, and to a lesser extent object characteristics (more specifically the mass of the object being manipulated). More succinctly, if an individual has an accurate knowledge of the environment, particularly for well-learned and practiced jobs, a meaningful consistency of stepping behaviors is observed within and between individuals. Furthermore, these stepping progressions can be represented by a concise set of scalable behaviors that are a significant subset of those observed for everyday activity. An important implication of this finding is that the simulation of a few common stepping patterns is sufficient to represent a large percentage of normal worker behavior.

3. Develop foot placement prediction models from laboratory data for commonly observed manual material handling transfer stepping patterns. The Transition Stepping (TRANSIT) model, which fulfills this objective, is described in detail in Chapter 4. The step predictions of the TRANSIT model are an important contribution to the research on manual materials handling. No previous studies have addressed foot placements for the breadth of task conditions considered in this study. These foot-placement predictions are critically important inputs for ergonomic analyses using human figure models. Another important contribution is the method used to quantitatively define the step placements of each behavior. The Q-TRACS method for parameterizing each stepping behavior (and individual step), originally described in Chapter 3, incorporates the previous and future requirements of the task sequence through approach and departure direction, which are shown in Chapter 3 to have significant effects on stepping behavior. In addition, the step of highest priority (i.e. the lead foot for terminal split stance postures) that constrains the whole body to an appropriate posture for subsequent analysis is used as a reference for other step predictions in the behavior. The prioritization used in the parameterization was supported in the data by the variance of the lead foot positions being on average less than
the variance of associated variables for other steps. In particular, the variance of the fore-aft distance of the lead foot and the object was substantially less for all the modeled behavior groups than the variance of the fore-aft distance between the step prior to the lead foot and the lead foot. The value of this parameterization is demonstrated by the fact that, after scaling for stature and grouping by transfer type and transfer hand, many (30.3%) of the step variables were invariant to the remaining task and subject conditions. Since all the step placements in Q-TRACS, excluding the lead foot during terminal stance, are defined with respect to another foot location, the structure of the model takes advantage of the correlations among step placements, permitting accurate predictions with relatively simple statistical models.

4. **Develop a framework for integrating cyclical and non-cyclical foot placements in the ground plane within a digital human modeling platform.** A framework for integrating separate step prediction models was proposed and implemented using the model described in Chapter 4 and a gait model derived from previous research. The framework tests the applicability of independently derived models in an integrated system and validates the potential for modeling and integrating action oriented stepping through separate component-level predictions. The development of the framework resulted in two major contributions. Firstly, a formal definition of the steps from each of the prediction models to be integrated that could be scaled to facilitate that combination was introduced. Principal and non-principal steps were defined to distinguish between the steps critical to the individual model and the steps used to facilitate the position of those critical steps. For the implementation used in the dissertation, the lead foot at the terminal split stance was defined as a principal step for the transition behaviors with the remaining steps defined as non-principal. All the steps from the gait model are defined as non-principal. Secondly, a method for representing the observed phenomenon from the laboratory study in which equivalent split stance behaviors were utilized depending on the distance traveled to the manipulation target was implemented. The flexible step scaling implementation modeled the observed change in lead foot for different overall distances traveled and introduced the necessary parameters for modeling the observed preference (laboratory and industry studies) for contralateral lead foot transition behaviors. Potentially of greater importance, the construction of this
framework lends support to studying, understanding, and modeling task-oriented stepping independent of upper body motion. Step prediction models for different action oriented tasks that are based on different underlying principles (i.e. models where different biomechanical factors may be emphasized) can still be used in concert to develop robust stepping models for simulating stepping patterns not limited to a small number of highly constrained actions.

6.5. Limitations

Field Study

The automotive assembly plant study was conducted to characterize the frequency of transfers and associated stepping patterns of experienced operators performing manual material handling transfer tasks. The results of the field study are limited in several ways:

- The population of the operators studied was not controlled. Five times the number of men versus women were observed (25 men, 5 women) limiting the generalizability of results across gender. As expected, the average male stature of the studied operators was also significantly taller (by approximately 0.2 m) than the average female stature. Similar relationships were also observed with mass. Operator strength was not measured or considered.
- The majority of operators were observed from a single shift (morning).
- The operators observed were all United Auto Workers (UAW) labor union members.
- The type of footwear worn by each operator was not controlled.
- Protective eyewear was required for each operator, although the type (i.e. glasses, goggles) was not controlled.
- The operator/object coupling was not measured or classified and assumed to be similar across transfer operations. Actions used to reposition the part prior to the lifting or delivering were not included. The operators were also required to wear cotton work gloves as protective equipment.
- The lifting hand(s) for each transfer task was self-selected by the operator and not controlled.
• Only a small number of operators (~1%) and jobs (~8.5%) performed in the assembly plant were analyzed. Jobs in this convenient sample were chosen to facilitate the analysis of manual material handling transfer tasks. Tasks with clear sight lines for video analysis and those involving discrete materials handling actions were more likely to be selected. No comparison between different workers performing the same job (or the same worker performing the job multiple times) was conducted.
• The results are from experienced operators in an automotive assembly plant and may not be applicable to other work environments.

Laboratory Study

The laboratory study was conducted to characterize the relationship between self-selected stepping patterns used during manual material handling transfer tasks and the requirements of the task and worker characteristics. The results of the laboratory study are limited in several ways:
• Only 20 subjects (10 men, 10 women) were analyzed. A larger sample would provide more statistical power for examining the effects of subject covariates and task variables. However, the sample size was large enough that any effects not observed in this study are likely to be small relative to those that were observed.
• The demographics of the laboratory participants consisted primarily of young (college age) fit individuals and may not be representative of the operators observed in the plant study or of any particular application population. Additionally, the laboratory participants should be considered novice manual material handlers (as compared with the experience of the plant study operators). However, each laboratory participant practiced the transfers analyzed and were knowledgeable to the tasks performed, and the consistency between the behaviors observed in the plant and laboratory suggest that the data are comparable.
• The transfers were conducted in a laboratory environment. Twenty-nine retro-reflective markers were affixed to each participant, potentially limiting the range of motion of the subject or affecting his or her
movements. The study was conducted on a raised (~3”) wooden platform with force plates located in the floor. The subjects were instructed to ignore the force plates. However, the change in compliance between the floor and force-plate was noticeable. The coefficient of friction of the floor was not recorded, but may have affected behavior.

- Tasks requiring significantly more time to complete than the ones studied here may not be characterized by the same distribution of transfer behaviors (i.e. single limb ground contact terminal split stance strategies).
- The type of footwear worn by the participants was not controlled. Subjects were instructed to wear comfortable shoes. Most wore athletic shoes. The use of other footwear, such as heavy boots, might have affected the results.
- For purposes of analysis, the paths followed by the participants between the start, transfer tower, and end locations were assumed to be straight. However, actual performance during each trial may have deviated from the idealized condition.
- Hand/object coupling was designed to not be a limiting constraint on the task. The one-handed vertical cylinder objects were outfitted with a rubber stopper limiting the requirement of grip strength to hold the object. The two-handed objects were lifted using horizontal cylinders attached to either side of the box. Participants were instructed which hand(s) to perform the transfer. More complex or difficult coupling could alter the foot movement patterns. In particular, objects that required a longer period of time to grasp might produce different patterns of foot movement. Similarly, the laboratory objects were relatively easy to carry and did not interfere with the movements of the lower limbs and did not obstruct vision. Large objects might influence behavior through either of these mechanisms.
- For the one-handed transfer trials, the task of the contralateral hand (the hand not performing the lift) was unconstrained.
• All subjects used their right hands for writing and on that basis were characterized as right-handed. Left-handed participants might have exhibited different behavior.
• The participants had knowledge and experience lifting each object prior to the beginning of each transfer trial.
• The direction preference of turning for each participant was not recorded.
• Participants were not instructed on where to look during the trial.
• The laboratory environment was unobstructed with only the transfer towers as potential obstacles.
• The participants always started each trial facing the pickup location.

**TRANSIT Model**

The Transition Stepping (TRANSIT) model predicts the most probable stepping behavior based on a logistic model derived from the laboratory study and scales the steps in that behavior with empirical relationships derived from the same study. The TRANSIT model is limited in the following ways:

• The TRANSIT model only predicts step placements associated with an object pickup or delivery transfer. Step placements for tasks in which the worker remains stationary were not quantified.
• The model selects from five different stepping behavior groups; no other behaviors are modeled.
• The stepping behavior grouping scheme was chosen to facilitate limitations in the automotive plant study. Alternative grouping schemes are possible, and the choice of grouping would affect the number of behaviors that are judged to be prevalent. The current grouping was selected to provide a good balance between parsimony and accuracy. The choice of grouping was also influenced by the limitations of the video analysis methodology, particularly the difficulty in determining foot placements and orientations in terminal stance.
• The approach and departure vectors that define the turn angle used in many of the step variable regression equations were assumed to be straight
paths. In many applications, workers may move on curved paths when approaching or departing from a pickup or delivery point.

• The approach and departure angles, defined with respect to a global orientation of the object to be manipulated, were not included as potential regressors in any of the regression equations. The model assumes that the global orientation of the part with respect to the orientation of the body does not significantly affect the selection or scaling of the stepping behavior.

• The user must define which hand(s) to use to transfer the load. The model does not predict which hand a worker will use, or when a worker will chose to use both hands.

• A varied number and range of task conditions and anthropometric characteristics was used to develop the scaling equations associated with each step behavior. Potential predictors were included when they had statistically significant and meaningfully large effects. Both the identification of potential predictors and the choices of which to include in each model necessarily involved some subjectivity. Alternative models that produced similar statistical fit could be created. The regression models should not be interpreted as representing causal relationships.

• The logistic model used to select a stepping behavior group was not validated against an independent source of data.

Integrated Stepping Model

The Integrated Stepping Model (ISM) proposes a method for integrating the spatial step predictions from independent step placement models. The ISM also defines a method for predicting the temporal foot events (i.e. heel lift, toe lift, heel contact, and toe contact) from kinematic constraints and empirical timing relationships from the laboratory study. The ISM has the following limitations:

• The method for representing and integrating independent stepping models was validated for general tasks and has only been applied to two stepping models, the TRANSIT model and a cyclic walking model derived from literature values.
• The ISM does not include a method for automatically selecting which independent stepping model (e.g., TRANSIT) is appropriate. The user must currently select an appropriate model.
• The method for identifying the order of foot events (i.e. heel lift, toe contact, etc.) by the sequence and location of the foot placements has not been validated.
• The ISM timing model is primarily empirically based and has not been validated beyond the original dataset used to fit the model.
• Paths are currently defined simply (as straight lines) and more realistic paths involving curves are not implemented, although the model structure anticipates the development and implementation of curved-path walking and turning at points other than those involving MMH tasks.
• The ISM requires as input a sequence of the tasks to be performed. In addition, accurate knowledge of each task and the work environment and the tasks are to be performed (e.g., the weights of objects, number of hands to be used) is required.
• The step integration/scaling strategy has not been validated. However, it replicates two important components observed from the laboratory study identified as (1) final step scaling and (2) stepping behavior transition.
• The ISM user must identify if two input tasks overlap, with respect to the predicted principal steps, and select a new step prediction model that is more appropriate. That is, the current implementation requires at least one gait stride between two transition stepping patterns.

6.6. Future Research

The findings of this research, along with its limitations, identify several areas for future work.

1. The Lexical Transition Classification System (L-TRACS) was shown to be useful for identifying, classifying, and modeling the stepping patterns used during manual materials handling (MMH) transfer tasks. A grouping scheme of the L-TRACS behaviors was further used to reduce the number of unique stepping patterns into a manageable and concise set that reasonably spanned the observed set of stepping
strategies. Five of those behaviors groups accounted for 71% of the observed stepping strategies in the laboratory study for the transfer tasks studied. However, the grouping scheme combined behaviors with the common attributes of 1) number of steps, 2) lead foot during the terminal stance, and 3) the sequence of steps. The choice of characteristics on which to group was influenced by methodological limitations in being able to accurately assess step attributes, particularly the type of step and terminal stance ground contact state. Other grouping schemes could be developed that better associate certain behaviors and task conditions or improve the overall performance of the multinomial logistic model used to predict behaviors. One potential scheme would group behaviors with the same ground contact state of the feet during terminal stance. This strategy may be used to better predict behaviors to match task conditions for which a single limb stance strategy, as compared to when both feet are on the ground when the load is manipulated, was used.

2. Subject factors had only small effects on selection and execution of the most frequently observed stepping behaviors after scaling for subject stature and body mass. One potential explanation of the lack of anthropometric effects on step scaling and selection may be attributed to only stature and BMI being used as subject descriptors to characterize the laboratory participants. Additionally, those subject descriptors were used to normalize measures with the same dimension (e.g. step distances were normalized by stature and the normalized values were predicted), effectively modeling a linear effect with no intercept prior to statistical analysis. Previous studies have suggested that experience and physical capability may influence stepping patterns when performing MMH tasks (Authier et al., 1996; Delisle et al., 1999). The functional limitations associated with advanced age have been shown to affect the number of steps used to perform a 180° turn (Lipsitz et al., 1991). However, the distribution of stepping behaviors observed in the industry and laboratory study does not support the hypothesis that experience (or age) significantly affects the selection of stepping pattern when performing the type of transfer tasks studied here. The difference among within and between subject variance for select step variables (particularly the fore-aft distance of the lead foot and the object) suggests that intersubject variability is important, but that
variability does not appear, in the current data, to be related to overall body dimensions. Research including a broader spectrum of subject factors including range of motion, experience, age, and strength may help explain the behavior selection process and reduce the variability associated with the between subject variance. However, a model including those effects would not be of general use for ergonomic simulation unless distributional data for those additional predictors was available for the population of interest. For example, hip range of motion might affect stepping behavior, but because no data on hip ROM for auto workers is available, that variable would not be useful as a predictor in a motion simulation model for auto ergonomics applications.

3. The transitioning from cyclic to action directed MMH steps is modeled in the Integrated Stepping Model as a hybrid strategy in which steps are scaled to accommodate the lead foot position at the transition and, if that alone is not sufficient, a change in lead foot (i.e., a change in behavior pattern) is used. An equal preference is given to left and right lead foot strategies under the current implementation. However, the laboratory and industry study both suggest that a lead foot strategy in which the foot opposite the direction of turn is preferred. A study focused on the scaling patterns and strategies of the steps used to accommodate the position of the lead foot may not only produce more realistic step simulations, but also provide insight into the motor control and planning aspects of how people plan their steps when performing action directed MMH tasks.

4. A method for empirically modeling the timing of the foot events when only the foot positions and sequence of steps defined by initial contact are known was presented. The timing of the foot events involving a swing phase was modeled statistically after normalizing those times by an associated pendulum period defined by leg length and swing distance. The models were primarily statistical fits from data and can be considered self-validating with respect to the available data. However, a comparison to published step times, particularly for predicted gait steps, may provide a method for linking the timing model with previously published research. Potentially of greater interest is the comparison of the results of the ISM timing model as compared to
accepted and utilized methods for determining job demand times (i.e. MTM). A study that compares actual human performance timing during MMH tasks, the results from the newly proposed ISM, and the estimates from currently available timing models would quantitatively assess the performance of the ISM timing and the improvements in estimating job cycle times with the new method over the currently available techniques. Importantly, digital human model simulations often must be performed using prescribed task times. Future research should investigate the extent to which the current findings with regard to timing, behavior selection, and step placement are robust to time requirements. In general, the workers in the laboratory study appeared to move more quickly than the auto assembly workers in the field study, probably because the cycle times in the plant were prescribed to allow a worker to perform for 8 or more hours.

5. The current implementation of the ISM is limited to MMH transition tasks for light to moderate loads (< 13.61 kg, or 30 lbs) in task conditions that involve minimal posture restrictions. Although these types of MMH tasks are prevalent in industrial settings (Baril Gingras et al., 1995; Lortie et al., 1996), other stepping models are required to fully capture the breadth of activities performed by industrial operators. For example, the consequences of obstructions that limit how close the feet may be placed to the object have not been examined. Potentially the most useful generalization of the modeling methodology presented here would be in predicting the step placements for pushing and pulling tasks. With the prevalence of MMH lift assist devices being used for heavier object transfers, including such action directed steps in the ISM would greatly improve the range of jobs and potentially complete job cycles the ISM could simulate. Step predictions that are of interest to work cell simulations as well as more general situations that a similar methodology used in this dissertation can be applied include turning while standing in place, turning during cyclical walking, walking while carrying a load, gait initiation, and gait termination.

6. The prevalence of transfer tasks being performed with single limb support when equivalent strategies in which both feet are in contact with the ground suggests that static stability is not a primary concern for these tasks. Postural models such as the one
proposed by Gonzalez et al. (1999) that find equilibrium postures in which the stability margin is maximized may not be appropriate for the common tasks addressed in the current work. The high prevalence of single limb support transfers, particularly when a large change in direction is required, suggest that people exploit dynamic balance to facilitate the change in direction. This observation can be further interpreted as a strategy in which conserving energy (when on one foot) may be a primary objective. Passive dynamic models, similar to those being used to prescribe cyclic gait in which a minimum amount of energy consumed (McGeer, 1988; Bauby et al., 2000; Kuo, 2001), may be a useful approach for understanding the kinematics of the pelvis with respect to the stance foot for the single limb support transfer tasks. Even a relatively simple inverted pendulum representation of the whole body performing the transfer task during single limb support may provide insight into the potential benefits over other behaviors associated with single-limb-support turning strategies.

7. The coordination between step timing and when the load is initially borne by the operator (for pickup tasks) are not obviously constrained when an even stance is used (feet adjacent to each other). In the ISM implementation, an even stance strategy can be used for a task that requires a relatively long amount of time to complete. This was supported qualitatively by observations in the industry study. When operators had to perform operations at a workstation requiring more than a few seconds, an even stance was always used. However, the same decoupling between step and pickup timing does not seem to hold true for single limb stance transfer strategies. Considering the prevalence of the single limb stance strategy, a future study that focuses on accurately modeling the relationship between task duration and stepping pattern would be helpful in accurately predicting the whole body terminal posture used during the object pickup.

One strategy that has been previously explored in the study of human movement that may potentially explain the relationship between step and pickup timing utilizes the principal of minimum jerk (reducing the rate of change of acceleration). When applied to the lifting problem described here, the data suggest that the pickup time may be chosen so that the dynamics of the body are minimally perturbed by the addition of the mass of the lifted object. This time corresponds to the instant when the center of mass (COM) of the
body is at a minimum speed or changing directions. The acceleration of the COM is instantaneously at zero, so the addition of mass to the body at this time has, theoretically, no effect on acceleration. The use of a minimum jerk strategy would also have implications toward the justification for utilizing static, quasi-dynamic, or full dynamic biomechanical analysis for ergonomic assessment. A minimum jerk strategy would suggest that a full dynamic analysis may not be needed to accurately estimate the stresses of the musculoskeletal system at the time of load pickup, and that a quasi-dynamic analysis (in which the equivalent dynamic external forces are applied to a static posture), or a static analysis (in which the inertial effects are not included) may be sufficient (Wagner et al., 2007).
6.7. References


