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Foot motions in manual material handling transfer tasks: A taxonomy and data from an automotive assembly plant

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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 analysed. A minimum of five cycles was analysed for each task. The approach angle, departure angle, hand(s) used, manipulation height and patterns of footsteps were coded from the video. Object mass 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 configuration of the lower extremities during terminal stance. Based on an analysis of the distribution of stepping behaviours 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 behaviour groups accounted for over 90% of the transition stepping behaviours observed in the assembly plant. Approximately two-thirds (68.4%) of the object transfers observed were performed with only one foot in contact with the ground during the terminal posture. The results from this paper suggest that a predictive model for choosing a transition stepping behaviour, coupled with a model to scale the selected foot behaviours, is needed to facilitate accurate prospective ergonomic analyses. This study proposes a method for categorising the stepping patterns associated with MMH tasks. The influence of task type and task sequence on the stepping patterns observed during several automotive assembly tasks is discussed. For prospective postural analyses conducted using digital human models, accurate prediction of the foot placements is critical to realistic postural analyses.

Keywords: manual material handling; lifting; step; taxonomy; transfer

1. Introduction

The prevalence of manual material handling (MMH) tasks in industrial settings is driven by the adaptability, flexibility and durability of human operators. The US Bureau of Labor and Statistics reported in 2004 that 5.1 million workers were classified under 'Manual Moving Occupations' and 2.43 million of those workers were specifically labelled as 'labourers and hand freight, stock and material movers' (Bureau of Labor Statistics 2006). The total number of individuals participating in MMH tasks in the workplace is probably under-represented by these statistics because materials handling is a part of many jobs that do not fall under this classification.

Many MMH jobs require the operator to perform a variety of standing work tasks. Standing work can be further partitioned into stationary standing work, in which the operator can primarily stay in one location, and non-stationary standing work, in which the operator is required to move about a work area, usually by walking or acyclic stepping. Baril-Gingras and Lortie (1995) analysed 944 MMH 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). Among MMH tasks, lifting in stationary standing work has received special attention over other tasks because of its prevalence in job sites across industries and association with injury (Bendix and Eid 1983, Gagnon *et al.* 1993, Dysart and Woldstad 1996, Burgess-Limerick and Abernethy 1998,

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Kollmitzer *et al.* 2002). Lifting in conjunction with non-stationary standing work 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). Several predictive models have been developed to generate postures for MMH tasks (Andres and Chaffin 1991, Ayoub and Lin 1995, Dysart and Woldstad 1996, Ayoub 1998, 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. Additionally, the current approaches for manikin posturing rely on the software user (ergonomist) to position the manikin and recent research indicates that these guesses are often substantially in error (Lamkull *et al.* 2006, Stephens and Godin 2006). No lifting models are known to have the capability to predict the unconstrained initial posture, as well as the lifting or transfer motions that 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 criteria (Chaffin and Baker 1970, Ayoub and Lin 1995, Ayoub 1998, Dysart and Woldstad 1996, Center for Ergonomics 2002, 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 analysed (Kingma *et al.* 2004, Wagner *et al.* 2005, Plamondon *et al.* 2006).

The goal of the current work is to quantify the patterns of foot motions for MMH tasks in automotive assembly, particularly those associated with non-stationary standing work. Previous work has addressed how such a classification could be implemented to improve the fidelity of motion prediction for use with digital human models (Wagner *et al.* 2006). Methods for quantifying and comparing physical task performance vary depending on the required level of precision. For kinematic comparisons, qualitative behaviour strategy descriptions (Delisle *et al.* 1999, Hase and Stein 1999), quantitative joint angle position, velocity and acceleration profiles (Winter 1995) and various postural rating schemes (Karhu *et al.* 1977, 1981, Corlett *et al.* 1979, Keyserling 1986) have been used. Qualitative descriptions of behaviour 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 of experienced vs. novice handlers performing self-paced lifts. Delisle *et al.* (1999) quantitatively compared two of the experienced and novice lifting strategies defined from that study and reported that the expert strategies either reduced the path of the centre of gravity of the lifter or reduced the asymmetry of the posture at the delivery when compared with the novice 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 characterises the set of feasible kinematic configurations. For example, grip posture vocabularies have been used to establish common terminology (Schlesinger 1919, Cutkosky and Wright 1986) for defining differing grip behaviours.

A similar vocabulary for lower extremity behaviours during MMH 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', 'parallel' and 'even' 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 *et al.* 2006). Unfortunately, the cyclical stepping vocabulary does not sufficiently describe many of the observed non-cyclical stepping behaviours and a similar comprehensive vocabulary has yet to be adopted. A classification taxonomy is proposed here that focuses on describing the non-cyclical stepping behaviours for MMH pickup and delivery tasks.

Attempts at classifying and analysing stepping behaviours for turning behaviours (Hase and Stein 1999, Meinhart-Shibata *et al.* 2005) and lifting transfer tasks (Holbein and Chaffin 1997, Delisle *et al.* 1999) have not resulted in widely used terminology, possibly because of the relatively narrow scope of these efforts. The field of motion and time study has produced several generic Methods-Time Measuremet (MTM) methods (MTM-1, MTM-UAS, MTM-MEK, MTM-B) and industry specific methods (MTM-HC Healthcare, MTM-C Clerical Activity) for recognising and classifying motion (see Maynard and Zandin 2001 for a review), but these have limited utility for uniquely identifying the actual motions used to facilitate the turn. The two available descriptors for classifying non-cyclical stepping motions in the MTM system are 'turn body', used for identifying 'a rotational movement of the body performed by one or two steps' and 'side step', for classifying 'a lateral motion of the body, without rotation, performed by one or two steps' (Narayan and Hancock 1968). These studies have focused on a single or small set of stepping patterns, and have not presented a formalised 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;
(3) quantifies the distribution of industrial foot motions under the new classification system.

2. Methods

2.1. Automotive assembly job analysis

2.1.1. The automotive assembly plant and operators

Automotive assembly plants assemble vehicles by moving the vehicle past operators' 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. 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. At the time of this study, the assembly plant, in which observations were carried out, employed 3039 operators working at over 350 operator stations. Some operators were seated or used manual material lift assists for particular tasks, but the majority of lifting and delivery was performed in standing operations without any mechanical assistance.

2.1.2. 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 masses handled, the number of total steps over a job cycle and the vertical range of manipulation locations within the job. Each job was videotaped while it was performed by the regularly assigned operator or the assembly line supervisor for that job. A minimum of five cycles was recorded for each job. Jobs were excluded if more than one operator was involved in the transfer or if a mechanical lift assist was utilised.

For analysis, each job was decomposed into a series of pickup, delivery, turn and action tasks. Nine variables (listed in Table 1) were used to define each task (see Figure 1 for an example). Only pickup and delivery transfer tasks are reviewed here and tasks that involved MMH devices were not included.

In all, 42 jobs from the production line of the automotive assembly plant were each videotaped for five job cycles. Each job comprised approximately seven tasks, so that a total of 1312 tasks was reviewed. Each task was reviewed by three experienced assessors and only tasks that were categorised by all raters as a transfer (pickup or delivery) are presented here, giving a total of 529 transfer tasks performed by 30 different operators in 32 different jobs.

2.1.3. Classification methodology

Three raters classified nine variables (Table 1) for 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 re-evaluate each task included on the comprehensive list for accuracy in variable identification and transcription. A consensus evaluation for each of the Table 1 task variables in the revised comprehensive list was constructed using the following two-step methodology:

(1) Automatically assign a consensus value to a task variable if:
    (a) concordance (nominal variables) between the three raters was achieved; or
    (b) the range (continuous variables) encompassing the three raters' coded values was less than a specified amount. Table 1 lists the maximum range allowed between the rater values for each continuous variable to be identified without a group discussion. If this condition was satisfied, the mean value of the three coded values was used as the consensus value.

Table 1. Descriptions of variables used to identify each transfer task.

Classification Variable	Range of Values	Variable Description	Maximum Allowable Range for Consensus Agreement
Task	a, ps, pl, pt, ds, dl, dt, t	The type of pickup, delivery or turn that is being performed. a (action) – action/manipulation (e.g. opening a door) ps (pickup stay) – approach, pickup part, stay/manipulate part pl (pickup leave) – at workstation, pickup part, depart pt (pickup transfer) – approach, pickup part, depart ds (deliver stay) – approach, deliver part, stay/manipulate part dl (deliver leave) – at workstation, deliver/set down part, depart dt (deliver transfer) – approach, deliver part, depart t (turn) – in stationary posture, reorient body to depart in new direction	N/A
Approach Angle	$-180 <-> 180°$ nan	The approach angle, referenced from the axes defined by the part (Figure 2). 'nan' is used for tasks that do not have an approach angle.	45°
Departure Angle	$-180 <-> 180°$ nan	The departure angle, referenced in a similar fashion as the approach angle (Figure 2). Angles for Turns are referenced as the change in angle from an initial posture to the final selected direction.	45°
Pickup/Delivery Height	Metres	Height from the floor of where the load is picked up or delivered.	0.2 m
Load Mass	Kg	Mass of the load being manipulated. *Load mass is obtained from the Job Information Sheet.	N/A
Manipulator Hand	Left, Right, Both	The hand(s) used to perform the pickup/delivery task.	N/A
Contralateral Hand Action	Support, Carry, other	Description of the action effort of the contralateral hand for one-handed tasks.	N/A
Lexical Transition Classification Sub-system Coding	See section 2.2	***L***-Vector identification	N/A
Turn Direction	Left, Right	Direction the pelvis rotates during the lifting manual material handling event.	N/A

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

The approach and departure angles for each task were defined using the manipulation axes (X_M, Y_M), as shown in Figure 2. The manipulation axes were defined by the nominal even 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), that is, with the worker 'facing' the job. The manipulation axes were 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°.

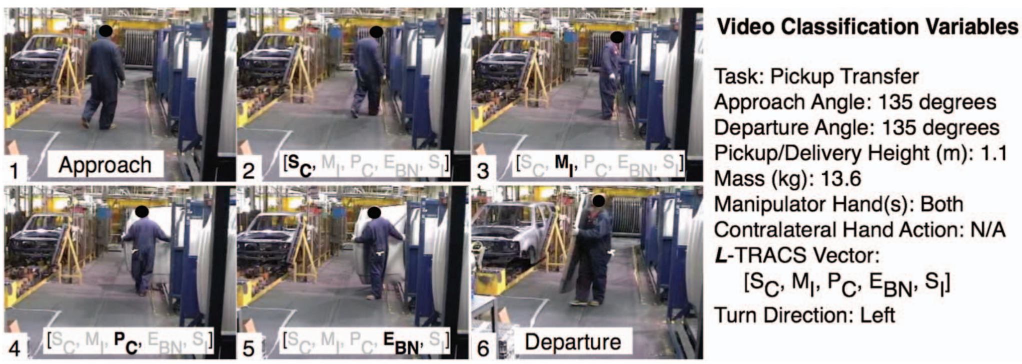

Figure 1. Representative video clip of a pickup transfer task and the associated classification values. Pictures are presented chronologically (1–6).

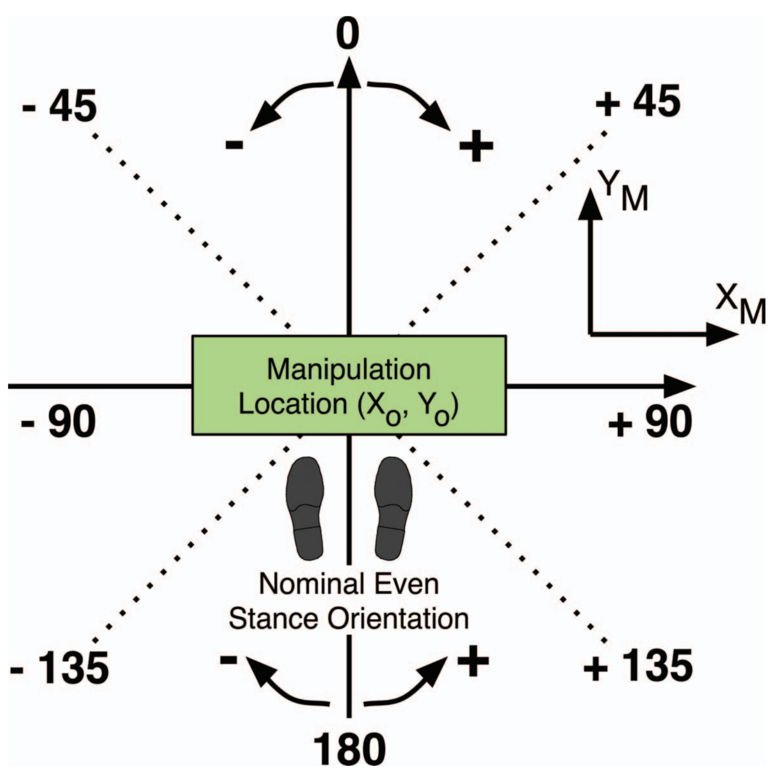

Figure 2. Pictorial representation of the approach and departure angle convention. Approach and departure angles are defined along the paths the approach and departure follow.

2.1.4. Statistical analysis

Two sets of 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 behaviours and the reliability of the independent raters for identifying those behaviours 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/).

Inter-rater reliability was assessed between the independent classifications performed by the raters and the subsequent consensus classification for each task variable. The intraclass correlation coefficient (ICC) was selected, based on guidelines proposed by Shrout and Fleiss (1979), to be a two-way single measure for absolute agreement reliability rating. Tolerances for the percent of raw agreement were set at 0.2 m for the height ratings and 45° 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'.

The kappa and the category-wise kappa statistics, used as measures for inter-rater reliability, are 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). 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'.

2.2. *Transition classification system for stepping behaviour*

An important observation of this research is that a large majority of foot behaviours in MMH tasks is 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 behaviours. Each TRACS representation of a stepping behaviour 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 representation of transition behaviour. L-TRACS is intended to be used for comparing and grouping behaviours with similar step progressions, while Q-TRACS uniquely defines the position and associated foot events for each step within a behaviour (Wagner *et al*. 2006). The formulation of L-TRACS is presented in the present paper.

2.2.1. Lexical transition classification sub-system

The lexical transition classification sub-system is a method for qualitatively describing a transition-stepping behaviour. 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 regard to the load position at the instant of pickup or delivery (i.e. when the mass of the object is initially borne by the lifter (pickup) or by the target location (delivery)). Ipsilateral and contralateral limbs are defined with regard to the turn direction. For example, a right turn (clockwise from above) defines the right lower extremity as the ipsilateral limb. A split terminal stance (feet spread apart as seen in the double support phase of a gait cycle) and an even terminal stance (feet side by side) are defined in further detail in the L-TRACS lexicology with ground contact information on the heels and toes at the lifting MMH event. This combined terminal stance and ground contact state is defined here as the terminal posture state.

2.2.2. The L-vector and step definition

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

$$L = [\Sigma_p, \rho, \Sigma_s],$$

where Σ_p and Σ_s describe the steps preceding and succeeding, respectively, the terminal posture state described by ρ. Σ_i is a sequence of steps given by:

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

where σ_j represents a step. The subscript {I, C} indicates whether the step is performed by the ipsilateral or contralateral lower extremity (Table 2). The order of steps in Σ_i is sequential in time such that the time of the first foot contact event for step σ_i is strictly less than the time of the first contact event of step σ_{i+1}.

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

Table 2. Characters concatenated to represent a single step. A step comprises one step class element and one subscript foot element.

Step Character	Element Description
S : Progression P : Pivot O : Orient M : Move	Step class element
I : Ipsilateral foot C : Contralateral foot	Subscript foot element

heel segment of the foot. The four types of foot events are:

(1) Heel contact (HC)
(2) Toe contact (TC)
(3) Heel lift (HL)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, respectively, contained within the current step.
(5) If a HC or TC foot event occurs, the next heel or toe foot event, respectively, must be a lift. The contact and lift do not need to occur in the same step.

This representation of a step can also be used to quantitatively parameterise bipedal ambulation (Wagner *et al*. 2006). Due to the limitations of the data collection methods in the present study, the steps of the observed transition behaviours could not be identified in a similar fashion.

2.2.3. Definition of a lexical transition classification sub-system step

The core of the L-TRACS system is the definition of a step. Transition stepping behaviours 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). 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 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 HC, TC, HL and TL.
(3) One of the following step length and angle criteria combinations (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*(foot length)
      (ii) 30°
   (b) Small minimum step length and small allowable included angle:
      (i) 1*(foot length)
      (ii) 10°
   (c) Large minimum step length only:
      (i) 4*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

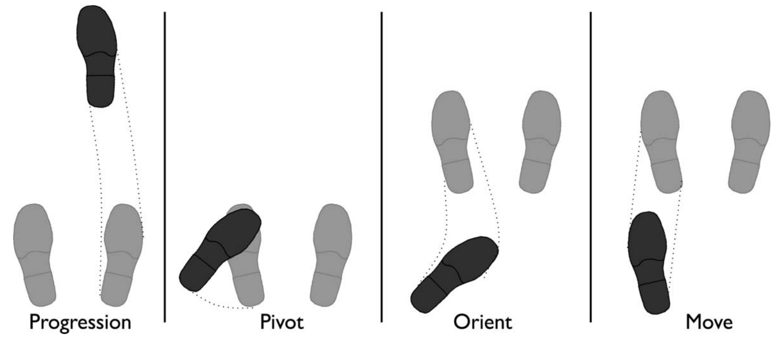

Figure 3. Examples of the four lexical-transition classification sub-system step types.

and distances of sequential steps from video recordings, it was difficult to identify one single criterion 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 HC event occurs before a TL 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° 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° 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 to the criteria above for defining the sequence of steps prior to the terminal posture state (Σ_p) occurs when defining the first progression step of a behaviour. The exception occurs for the second criterion, which states that progression steps must follow the foot event sequence of HC, TC, HL, TL. However, in certain cases, the HL and TL 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 behaviours 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 $\mathbf{\Sigma_d} = [P_C, S_I]$ is read from left to right as 'a pivot step with the contralateral foot followed by a progression step with the ipsilateral foot'. This $\mathbf{\Sigma_d}$ sequence is graphically depicted in Figure 4(B) in which P_C and S_I are labelled as steps 3 and 4, respectively.

When the foot visually 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 not being in contact with the ground.

2.2.4. *Terminal posture state*

The terminal posture state ρ represents the terminal stance and ground contact state of each foot at the

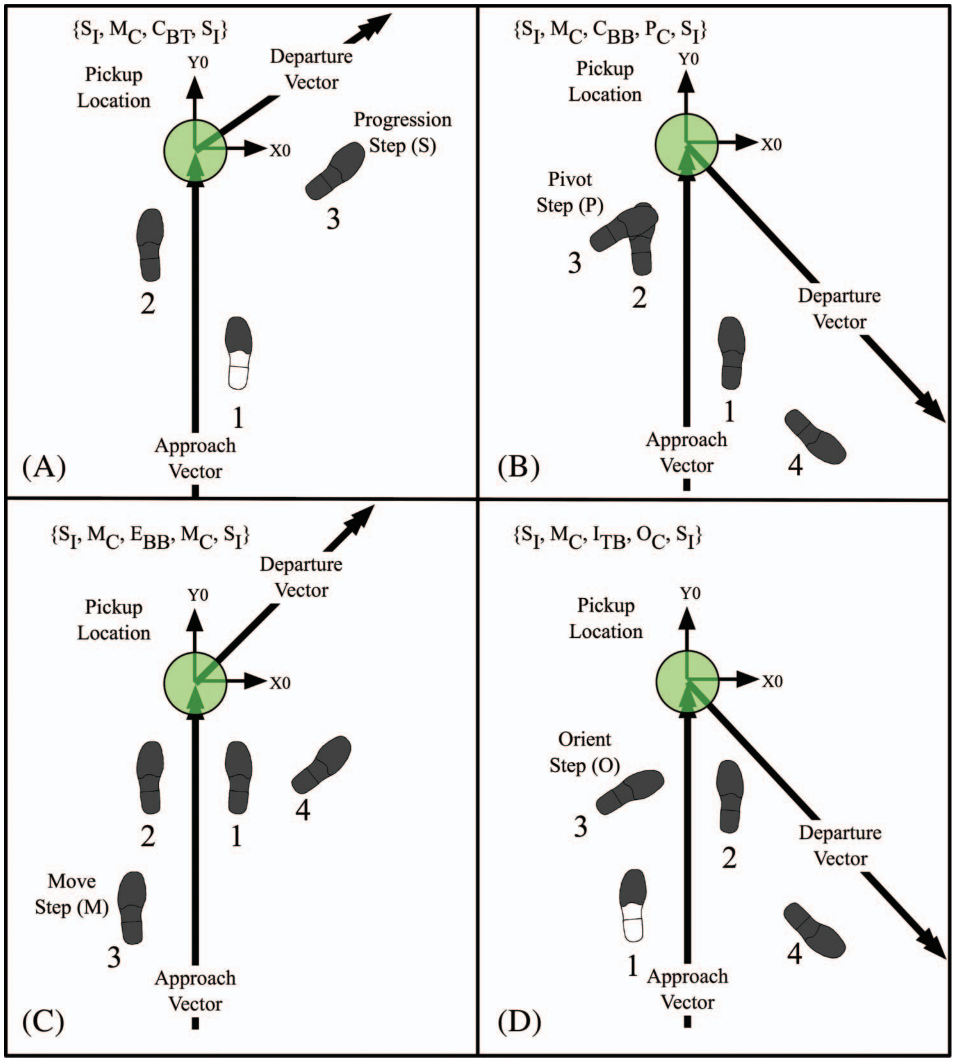

Figure 4. Examples of the four step class elements. Steps are numbered in the order in which they first contact the floor. The terminal stance is represented by steps 1 and 2. Load pickup occurs in the time between steps 2 and 3. All turns are to the right. The shaded area of the foot print represents contact with the ground. The lexical transition classification sub-system (L-TRACS) vector is given in brackets {} for each example.

lifting MMH event. The terminal posture state ρ is given by:

$$\rho = [\tau_{\gamma C, \gamma I}],$$

where τ is a terminal stance element {I, C, E} (Figure 4) and γ_C and γ_I are terminal stance contact element subscripts giving the ground contact status for the contralateral foot and ipsilateral foot respectively (Table 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 τ. 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 elements γ_C and γ_I define 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 regard to the direction of turn) as the lead foot, both the heel and toe of the contralateral foot contacting the ground {B} and the toe of the ipsilateral foot on the ground with the heel lifted up {T}. Examples of four transition behaviours and the associated L-TRACS representations are depicted in Figure 5.

Table 3. Characters concatenated to represent the terminal posture state. A terminal posture state comprises one terminal stance element and two subscript terminal stance contact elements.

Terminal State Character	Element Description
I : Split stance, Ipsilateral lead foot C : Split stance, Contralateral lead foot E : Even stance	Terminal stance element
T : Toe ground contact only H : Heel ground contact only B : Heel and toe ground contact N : No ground contact	Subscript terminal stance contact element

3. Results

3.1. 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 mass, 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

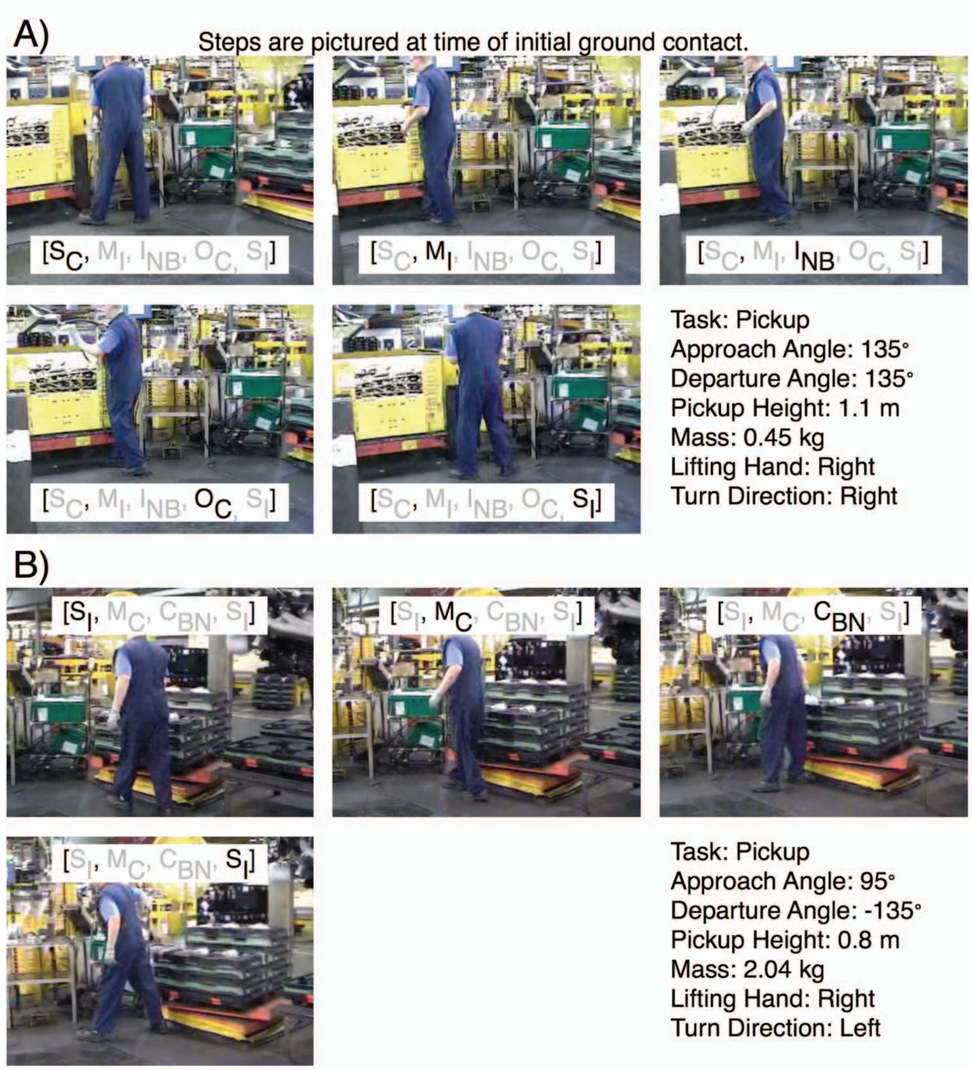

Figure 5. Examples of four transition behaviours observed in the assembly plant with select rated measures. The lexical transition classification sub-system (L-TRACS) description for the behaviours are: A) $S_CM_II_{NB}O_CS_I$; B) $S_IM_CC_{BN}S_I$; C) $S_IM_CE_{BB}S_I$; D) $S_IM_CE_{BN}S_I$.

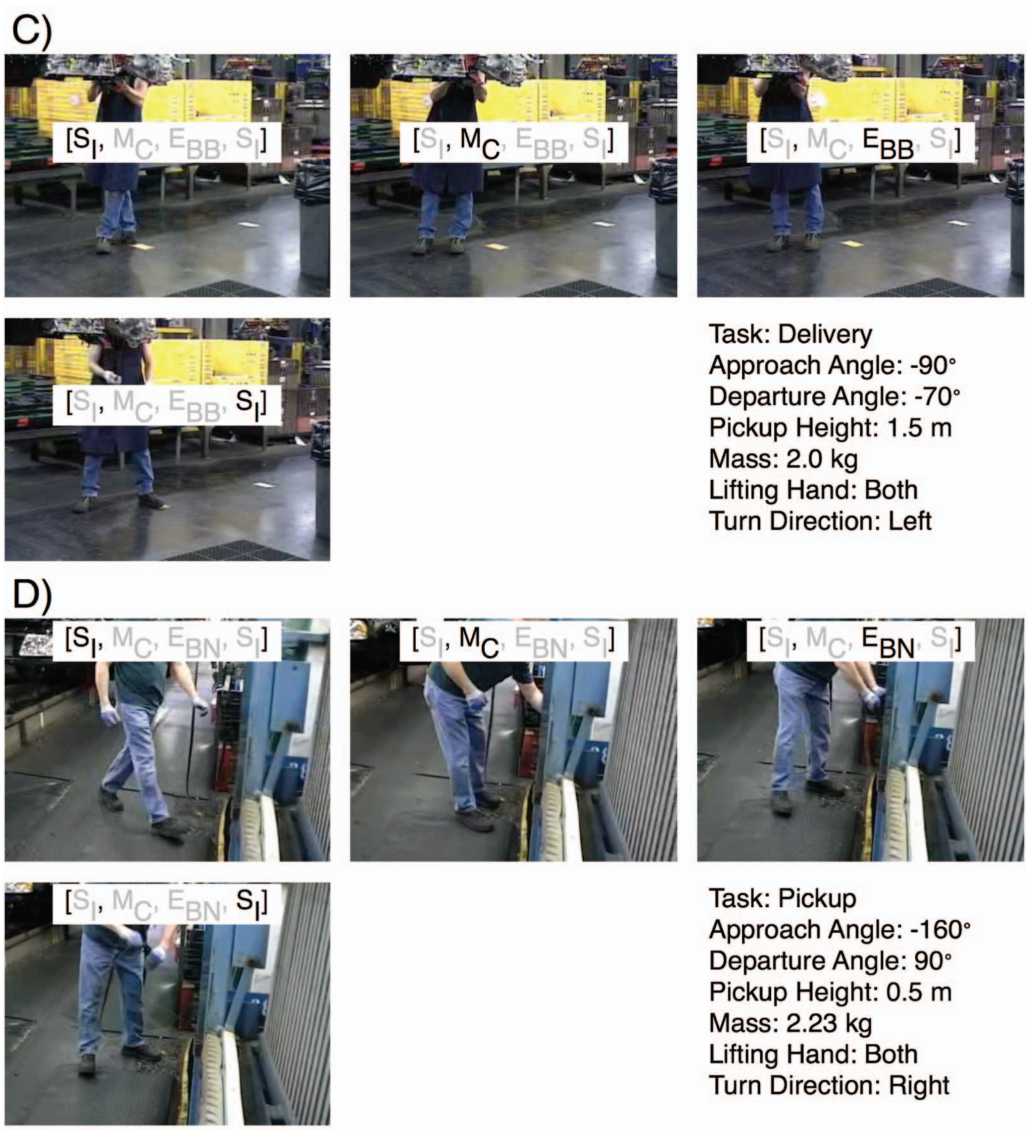

Figure 5. (*Continued*).

the contralateral hand is presented to describe the behaviour and/or constraints imposed by the opposing hand during the manipulation task. The inter-rater reliability is presented for each task element.

3.1.1. Operator statistics

In total, 25 male and five female experienced operators, ranging in age from 27 to 55 years, were observed performing 32 automotive assembly jobs. The level of experience varied across operators. Each operator's primary job (i.e. the operation on which the majority of their time is spent) was the operation or direct supervision of the operation under observation. Summary statistics (mean $\pm$ SD) for male and female operator characteristics are, respectively: stature (1.793 $\pm$ 0.083 m, 1.596 $\pm$ 0.086 m), mass (92.8 $\pm$ 15.2 kg, 66.8 $\pm$ 8.5 kg) and BMI (28.8 $\pm$ 3.9 kg/m^2, 26.2 $\pm$ 2.2 kg/m^2).

3.1.2. Object configuration, height, mass, 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 frequencies of the six classes of transfer (pickup/delivery for left/right/both hands) are presented in Table 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%).

The distributions of masses of the objects lifted are shown in Figure 6 for one-handed and two-handed pickup and delivery transfers. The majority of parts and tools transferred were of negligible mass (i.e. screws, fasteners, clips, etc.) and are represented here as having a mass of zero. The majority of one-handed transfers consisted of parts of negligible weight, while 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.

The distributions of manipulation heights are shown in Figure 7 for one-handed and two-handed pickup and delivery transfers. 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. One-handed pickup manipulations spanned the entire observed manipulation height range. Two-handed pickup and one- and two-handed delivery manipulations were observed to span only a 1 m range.

Table 4. Frequencies of the observed transfers classified by manipulation type and hand.

	Pickup			Delivery		
Measure	Left Hand	Right Hand	Both Hands	Left Hand	Right Hand	Both Hands
Frequency Count	60	174	115	17	31	132
% total within pickup or delivery	17.2	49.9	33.0	9.4	17.2	73.3
% total overall	11.3	32.9	21.7	3.2	5.9	25.0

3.1.3. 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) defined by the part and work-cell layout geometry. Angular probability density distributions (rose plots) for the approach, departure and included transfer angles are presented in Figure 8 for the pickup and delivery task conditions. Angular bin sizes of 18° are used for each histogram. References to each angular bin are made with regard to the angular value bisecting that bin.

Approach occurred most frequently along the 180° direction for the pickup (27.5%) and delivery (34.4%) transfer tasks (Figure 8). 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.

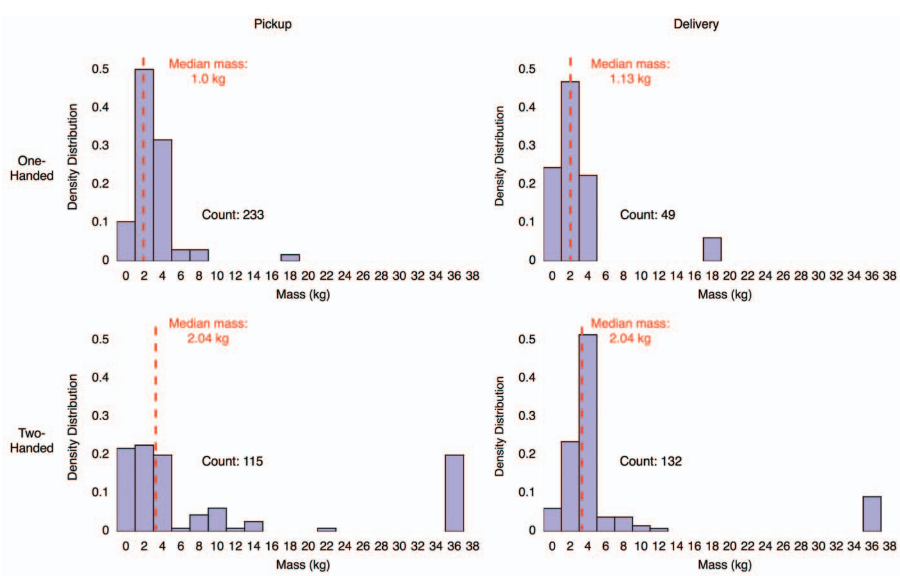

Figure 6. Object manipulation mass for one-handed and two-handed pickup and delivery transfer tasks.

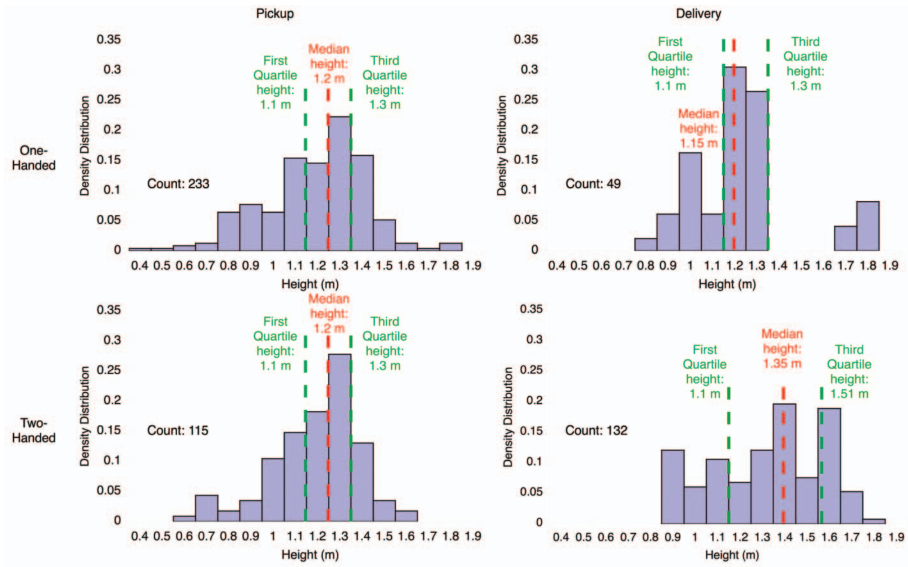

Figure 7. Object manipulation height for one-handed and two-handed pickup and delivery transfer tasks.

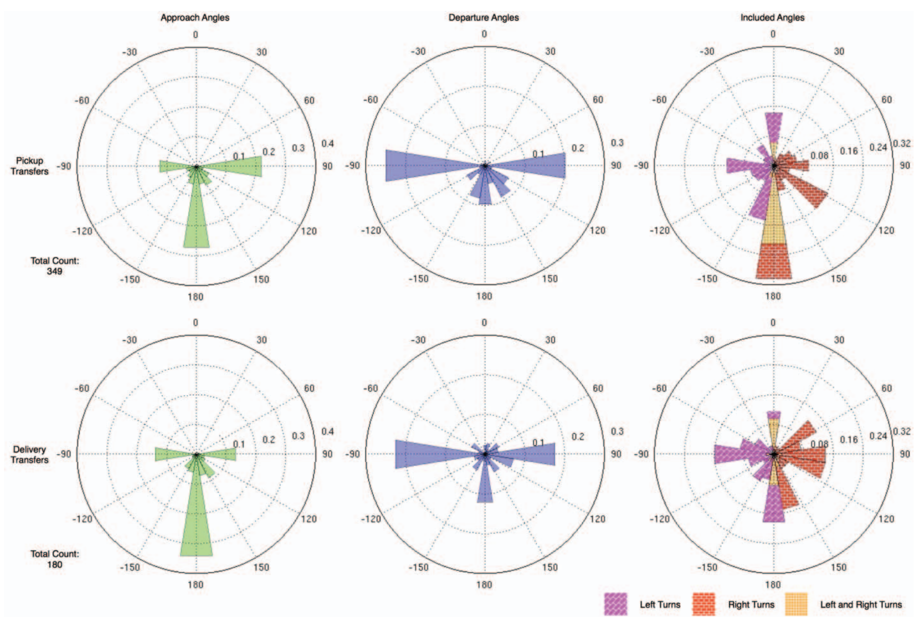

Figure 8. Approach, departure and included angle histograms classified by manipulation type (pickup and delivery) and turn direction (for included angles only). Included angle histograms for the left and right turn directions are presented on the same plot. Angular bins (n = 20; each spanning 18°) are used.

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 8). 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°. A total of 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 8). For example, a transfer with a left turn direction (counterclockwise) and approach and departure angles 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 8 as counterclockwise and clockwise angles respectively. Counterclockwise angles are defined here as negative. In total, 54.2% and 48.3% of the transition turns were toward the left direction for the pickup and delivery transfers respectively and 9.0% and 8.1% of the included angles for the left and right turn directions, respectively, for the pickup transfer tasks were greater than 180°. 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. In total, 9.2% and 6.5% of the included angles for the left and right turn directions, respectively, for the delivery transfer tasks were greater than 180°.

3.1.4. *Contralateral hand*

Of the one-handed transfers, 19.7% occurred with a contralateral 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 regard to that hand. The majority of the contralateral hand efforts occurred during pickup transfers (91.3%). Contralateral handed carry efforts (i.e. when 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 contralateral effort. Contralateral handed support efforts (i.e. when 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 contralateral effort. Right- and left-handed contralateral efforts occurred in 36.0% and 22.3% of all right- and left-handed transfers respectively.

3.1.5. *Inter-rater reliability*

The percent of raw agreement, the ICC (Shrout and Fleiss 1979) and the 95% CI on the ICC are presented in Table 5 for the continuous variables (manipulation height, approach angle, departure angle and included angle) classified to describe each task. Object mass was not evaluated because those values were provided by the assembly plant and not evaluated by the individual raters. 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.

Inter-rater reliability measures of the percent of raw agreement, kappa statistic (Fleiss 1971), and the category-wise kappas are presented in Table 6 for the nominal variables (task type, manipulator hand, step direction and step behaviour identification) rated to describe each task. Inter-rater reliability among the three raters was 'excellent' as defined by Fleiss (1981) and 'substantial' to 'almost perfect agreement' as defined by Landis and Koch (1977) for the nominal task description elements of task type, manipulator hand and turn direction. Inter-rater reliability for the identification of the step behaviour is presented in section 3.2.3.

3.2. ***Transition classification system behaviours***

The types and frequencies of the observed patterns of foot movements, classified using TRACS, are presented. A grouping technique for the TRACS

Table 5. Inter-rater reliability of measurements for continuous variables.

Measure	Raw agreement (%)	ICC	95% CI
Manipulation height	73.4	0.728	0.693 < ICC < 0.760
Approach angle	72.5	0.782	0.753 < ICC < 0.809
Departure angle	65.0	0.709	0.672 < ICC < 0.743
Included angle	60.1	0.763	0.729 < ICC < 0.794

ICC = intraclass correlation coefficient.

Table 6. Inter-rater reliability of measurements for nominal variables.

Measure	Raw agreement (%)	Kappa	Category-wise Kappas*
Task type	91.7	0.884	a: 0.499 dl: −0.003 ds: −0.011 dt: 0.931 pl: −0.008 ps: −0.004 pt: 0.942
Manipulator hand	79.6	0.775	B: 0.759 L: 0.800 R: 0.854 Null: 0.322
Step/Turn direction	92.4	0.897	L: 0.914 R: 0.909 Null: 0.227

*See Table 1 for category descriptions.

behaviours was used that clusters the behaviours based on the number of steps, progression of steps and the terminal stance. Correct identification of a TRACS behaviour by the raters using L-TRACS is evaluated. Inter-rater reliability measures for classifying an individual behaviour and the behaviour group are presented.

3.2.1. *Lexical-transition classification sub-system behaviours*

A total of 38 unique L-TRACS behaviours were identified in the video analysis. The behaviour '$S_IM_CC_{BN}S_I$' was observed most frequently and accounted for 30.5% of the pickup and 29.3% of the delivery transfer behaviours (Figure 9). This L-TRACS code is interpreted as follows:

- S_I The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).
- M_C The step immediately prior to the terminal posture is a move step (S) with the contralateral foot (C).
- C_{BN} 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).
- S_I The first step following the load transition (pickup or delivery) is with the foot on the side of the departure direction.

A grouping scheme that assigns L-TRACS behaviours by 1) the number of steps, 2) the lead foot during terminal stance and 3) the sequence of steps (i.e. contralateral vs. ipsilateral) was then applied. For example, individual behaviours with the only difference being in the ground contact during terminal stance (i.e. $S_IM_CC_{BN}S_I$, $S_IM_CC_{BT}S_I$, $S_IM_CC_{BB}S_I$) was included in the same behaviour group. Another example includes grouping individual behaviours in which the only difference was the type of preparatory step used immediately following the terminal posture (i.e. $S_CM_II_{BT}P_CS_I$, $S_CM_II_{BT}O_CS_I$, $S_CM_II_{BT}M_CS_I$ were grouped together). For clarity, behaviour 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 behaviour group for the $S_IO_CC_{BN}S_I$ individual behaviour is $S_IO_CC_{BB}S_I$). Additionally, preparatory steps are all identified in the behaviour group using the orientation (O) step (i.e. the behaviour group for the $S_CM_II_{BT}P_CS_I$ individual behaviour is $S_CO_II_{BB}O_CS_I$). Five behaviour groups

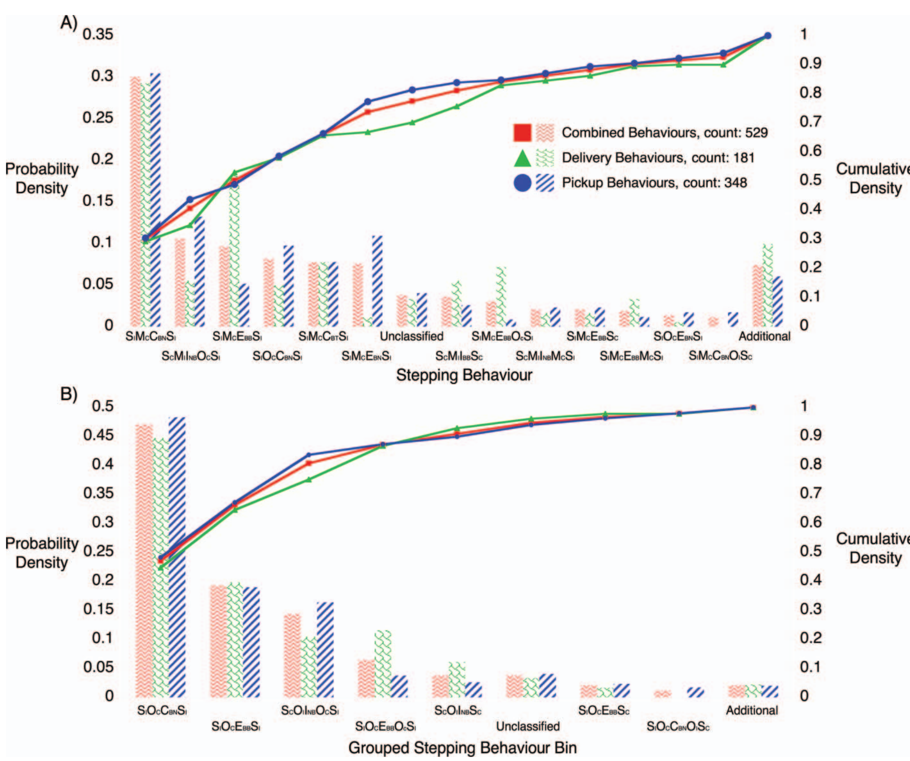

Figure 9. Individual (A) and grouped (B) lexical transition classification sub-system (L-TRACS) behaviours observed during the automotive pickup and delivery transfer tasks. The 'Unclassified' group is all transitions that were not rated with an L-vector. The 'Additional' group is all transitions that occurred as less than 1% of the total number of combined behaviours.

accounted for over 90% of all observed pickup and delivery transfer groups (Figure 9B). Behaviours accounting for less than 1% of the total observed transfers were further grouped together and are presented in the 'additional' category. A more detailed description of the five most common behaviour groups is presented in Table 7.

3.2.2. Lexical-transition classification sub-system elements

The number of non-cyclical steps used to perform a transition behaviour ranged from three to seven. The majority of observed behaviours used three or four 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 behaviours with the ipsilateral limb as the lead foot and the remaining 70% with the contralateral limb as the lead foot (Figure 10). 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.

Table 7. Step descriptions for the five most common behaviour groups.

Step Behaviour Group	Step or Terminal Posture	Step or Terminal Posture Description
$S_I O_C C_{BB} S_I$	S_I	The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).
	O_C	The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).
	C_{BB}	In the terminal posture, the contralateral foot (C) is forward.
	S_I	The first step following the load transition is with the foot on the side of the departure direction.
$S_I O_C E_{BB} S_I$	S_I	The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).
	O_C	The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).
	E_{BB}	In the terminal posture, the both feet are even (E) with one another.
	S_I	The first step following the load transition is with the foot on the side of the departure direction.
$S_C O_I I_{BB} O_C S_I$	S_C	The second-to-last step before the terminal posture is a progression step (S) with the contralateral foot (C).
	O_I	The step immediately prior to the terminal posture is a preparatory step with the ipsilateral foot (I).
	I_{BB}	In the terminal posture, the ipsilateral foot (I) is forward.
	O_C	The first step following the load transition is with the foot on the opposite side of the departure direction.
	S_I	The second step following the load transition is a progression step (S) with the ipsilateral foot (I) along the new direction of progression.
$S_I O_C E_{BB} O_C S_I$	S_I	The second-to-last step before the terminal posture is a progression step (S) with the ipsilateral foot (I).
	O_C	The step immediately prior to the terminal posture is a preparatory step with the contralateral foot (C).
	E_{BB}	In the terminal posture, the both feet are even (E) with one another.
	O_C	The first step following the load transition is with the foot on the opposite side of the departure direction.
	S_I	The second step following the load transition is a progression step (S) with the ipsilateral foot (I) along the new direction of progression.
$S_C O_I I_{BB} S_C$	S_C	The second-to-last step before the terminal posture is a progression step (S) with the contralateral foot (C).
	O_I	The step immediately prior to the terminal posture is a preparatory step with the ipsilateral foot (I).
	I_{BB}	In the terminal posture, the ipsilateral foot (I) is forward.
	S_C	The first step following the load transition is with the foot on the opposite side of the departure direction.

3.2.3. Lexical-transition classification sub-system identification and rater reliability

Inter-rater reliability measurements are presented for complete L-TRACS behaviours and the elements used to define those behaviours (Table 8). Agreement was defined for two individual L-TRACS behaviours if and only if the two behaviours have the same L-vector. Agreement was achieved for two grouped L-TRACS behaviours if the two behaviours belong to the same behaviour group. The chance-corrected agreement statistic (kappa) for individual behaviour identification was 0.326 and for grouped behaviour identification was 0.483. Rater agreements for the number of steps and terminal stance element were 68.2% and 56.3% respectively for all transfer trials. The category-wise kappas for the even, ipsilateral lead split and contralateral lead split stances were 0.573, 0.662 and 0.548 respectively. The individual L-TRACS kappa agreement was interpreted as 'fair'. The grouped L-TRACS, number of steps and terminal stance kappa agreements were interpreted as 'moderate'.

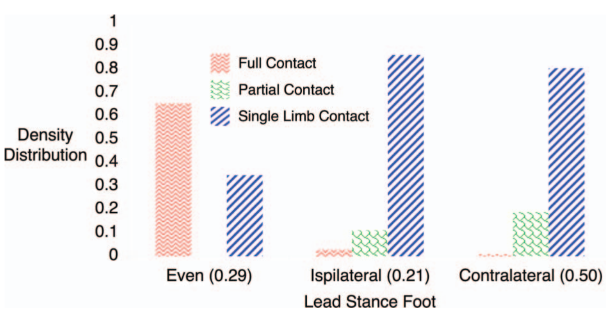

Figure 10. Distributions of the ground contact conditions for three terminal stances.

Table 8. Inter-rater reliability of measurements for lexical transition classification sub-system (L-TRACS) behaviours, groups and element variables.

Measure	Raw agreement (%)	Kappa (Fleiss 1971)	Category-wise Kappas
L-TRACS behaviour (individual)	24.8	0.326	*
L-TRACS behaviour (grouped)	46.9	0.483	*
Number of steps	68.2	0.557	3 steps: 0.593 4 steps: 0.694 5 steps: 0.197
Terminal stance	56.3	0.536	Contralateral: 0.548 Even: 0.573 Ipsilateral: 0.662

*Denotes more than 10 nominal categories.

4. Discussion

This study proposed a method for classifying transition stepping behaviours during MMH tasks and applied that system to identifying those behaviours used during selected jobs by operators in an automotive assembly plant. The tasks spanned a wide variety of manipulation heights, object type, object masses and floor layouts. Similar demands on human operators have been observed in other MMH studies across industries (Drury *et al.* 1982, Baril-Gingras and Lortie 1995). Ciriello *et al.* (1999) reported that, of the 3984 objects carried in a study spanning multiple MMH industries, over 73% of those transfers occurred over a distance of greater than 1.22 m. In the same study, a review of 10,101 lifting tasks revealed that 96.5% of those lifts started below a height of 1.143 m. In contrast, the pickup transfers in the present study had a median height of 1.2 m. This discrepancy may be explained by the continuation of the trend presented in the comparative study of lifting tasks over a 13 year period (ending in 1993), in which the median initial lifting height increased from 0.686 m (1981) to 0.762 m (1993) (Ciriello and Snook 1999).

The variety of job requirements combined with the infinite number of kinematically feasible stepping behaviours creates a large number of possible stepping patterns that could be chosen to satisfy the variety of task requirements. However, a relatively small number of stepping patterns (five L-TRACS behaviour groups) accounted for over 90% of the observed foot movement patterns. A single L-TRACS behaviour group accounted for over 30% of all observed behaviours.

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 and Eid 1983, Holbein and Chaffin 1997, Burgess-Limerick and Abernethy 1998). Sagittal plane lifts with no horizontal component are frequently studied (Ayoub and Lin 1995, Ayoub 1998), yet these represent a small portion of the lifts performed in industry (Baril-Gingras and Lortie 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 behaviour (Delisle *et al.* 1996, 1998). Studies in which the placement of the feet is unrestricted are rare (Authier *et al.* 1996).

Characteristics of representative worker-selected stepping behaviours 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 presented.

4.1. 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 behaviour in industrial tasks has also been previously documented by Ljungberg *et al.* (1989) and Authier *et al.* (1996). Yet, the important implications of this observation for proactive ergonomics analysis using digital human models have yet to be realised. In the authors' experience, analysts using digital human figure models nearly always use a posture in which the figure has two feet in contact with the ground when analysing a pickup or delivery task, and even stances (by the current definition) are much more commonly used than split stances (Stephens and Godin 2006). Wegner *et al.* (2007), in a discussion of future requirements for digital human manikin (DHM) software, highlights the need for more automated methods for posturing manikins to overcome the errors created by analysts using inaccurate postures.

The prevalence of single limb stance pickup and delivery transfers observed in the present study may be explained in part by the selection of tasks for observation. Negligible to moderately heavy load masses predominated in 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 behaviours where both feet are 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 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.

4.2. Terminal stance selection

Stepping behaviour terminal stance does not appear to be arbitrarily chosen by the operators. If the terminal stance for the split stance behaviours were arbitrary, the distribution of terminal stances for the split stance cases might be expected to be predominantly 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 behaviours were observed as ipsilateral lead foot behaviours. 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 and Chaffin 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 behaviour 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 behaviour, in which the ipsilateral foot is forward ($S_C O_I I_{NB} O_C S_I$). In this behaviour, 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 behaviours maintained the ipsilateral foot as the lead foot during the terminal stance. This result implies that 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 behaviour). 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 behaviour.

4.3. Number of steps to turn

The number of steps to effect a change in direction during a MMH transfer task could theoretically be very large, but the majority of transitions in the current study involved three steps. Studies characterising turning (Hase and Stein 1999) or addressing one or a few particular types of turns (Delisle *et al.* 1996) typically focus on turns in which two to four 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 behaviours with a small number of steps. The negligible and moderate load masses 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 minimise the loss of balance may promote transition behaviours 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 an 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 (in 65% of all trials) as the young population. Future work is necessary to quantify the trade-offs between balance, range of motion and energy, which affect the number and type of steps that workers use during MMH transitions.

4.4. Lexical-transition classification sub-system as a viable classification system for stepping behaviours

L-TRACS was developed to provide a rigorously defined, general purpose system for describing stepping behaviours for ergonomic applications. L-TRACS was able to classify the wide variety of pickup and delivery transition behaviours observed in the automotive plant, but L-TRACS is also able to accommodate behaviours 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 video-based observations.

L-TRACS is a categorical system for identifying and defining stepping behaviours, 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 a L-TRACS behaviour to be used in an ergonomic application with a human figure model (Reed and Wagner 2007). However, the complexity and high degree of variability of possible transition stepping behaviours have been impediments toward previous efforts of defining a language for turning behaviours being widely accepted. L-TRACS attempts to address many of these issues as a methodology for defining each step and terminal stance for transition behaviours. An integrated system known as Q-TRACS 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 that 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.

4.5. 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 achieving 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. Differing interpretations of 'sufficient' are one possible reason for the discrepancies in these nominal values that are traditionally easy to classify. The quality of the video also sometimes limited the correct identification of the ground contact elements for the terminal stance, leading to discrepancies between raters when differentiating between TC 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 (that is, tasks were excluded if at least two strides did not occur before and after the pickup or delivery), biasing the frequency of transfer tasks per job presented here compared to that occurring across the entire assembly plant. The limited range of load masses that were manipulated also limits the applicability of applying the observed stepping behaviours to situations where the manipulation of heavy loads may require stepping behaviours not selected here. The results presented here are primarily applicable to lifting MMH scenarios. The stepping behaviours 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 TRACS for classifying stepping behaviours would still apply.

The friction between the operator's shoes and assembly plant floor was not controlled or measured, which limits the applicability of these results when compared to other work environments. Of the 30 observed operators in the plant study, 24 were observed to be wearing sneakers, with the remaining operators wearing either boots or an unidentifiable shoe. The assembly plant floor where the observed MMH tasks were performed consisted of either a bare concrete floor or rubber matting. The friction of the floor has been identified as a critical determinant of lower extremity kinematics when walking (Cham and Redfern 2002) and for understanding slip hazards (Hanson *et al*. 1999, Redfern *et al*. 2001, Lockhart *et al*. 2003). Changes in the assembly plant floor friction may uniquely alter the stepping behaviours and frequency of occurrences even for operators performing similar MMH transfer tasks. However, the TRACS and the methodologies would still apply.

5. Conclusions

A methodology for classifying stepping behaviours that includes gait locomotion as a special case was developed and applied to identify worker behaviour in an automobile assembly plant. L-TRACS provides a standardised vocabulary for describing task-oriented stepping behaviours. Over 90% of the observed patterns of foot movement could be classified by five L-TRACS behaviours. Unexpectedly, the most common terminal posture for pickup or delivery of an object included having only one foot in contact with the ground. The results of this study emphasise the importance of developing accurate methods for simulating foot movement behaviours for proactive ergonomic analysis of industrial tasks using digital human models.

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Appendix 1: Glossary

Behaviour (Transition Stepping Behaviour) – The sequence of non-cyclical steps preceding and succeeding the terminal stance during a lifting manual materials handling (MMH) event.

Foot Event – The change in state of contact 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 a contact state with the ground. Lifts are defined as the transition from a contact to a non-contact state with the ground.

Lexical Transition Classification System – Categorical representation of a transition stepping behaviour. 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 MMH 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 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; rotate.

Non-Cyclical (or Acyclical) Stepping – A sequence of steps that cannot be characterised by a repeating cycle. The final state of the lower extremities for a non-cyclical stepping progression is usually different from the initial state.

Non-Stationary Standing Work – A subset of standing work that includes tasks requiring the motion of the lower extremities. Non-stationary standing work 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 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 toe lift or heel lift 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 – Quantitative parameterisation of a transition stepping behaviour. All the steps in each behaviour are represented with 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 – A subset of standing work that includes tasks where no locomotion between workstations is required. Stationary standing work requires no steps to be taken throughout the job cycle.

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

Transition Classification System – A method for describing and quantifying transition stepping behaviours. Lexical and Quantitative Transition Classification sub-systems define the descriptive and quantitative representations to facilitate behaviour selection and scaling respectively.

Transition Stepping – A subset of non-cyclical stepping, consisting of a set of behaviours used to enact a change of direction during a Lifting MMH event. Steps involved in transition stepping are classified here with the transition classification system.