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Predictive biomechanical analysis of manual material handling (MMH) transfers is dependent on accurate prediction of foot locations relative to the task. Previous studies have classified common acyclic stepping patterns used during those transfer tasks, but the influence of walking distance prior to the transfer is not well understood. Twenty men and women performed transfers for a minimum of six different delivery distance conditions. The number of steps used by the participants ranged from two to seven. A theoretical framework for idealised step-scaling strategies is proposed and compared with the experimental data. The maximum observed increase in step length prior to delivery was 1.43 times the nominal step length calculated for each participant. The data suggest that although participants can scale their steps to facilitate the use of a single terminal stance at the transfer, the majority of participants chose to utilise a combination of stepping strategies if the preferred contralateral lead foot strategy could not be easily implemented.

Practitioner summary: Accurate foot placements are needed for predictive biomechanical analysis of MMH. A laboratory study investigated the influence of previous step positions on MMH. A *flexible step-scaling strategy*, in which step lengths and strategy were varied, suggests that analysis based on simulated movements should consider multiple lifting postures.

Keywords: manual material handling; lifting; step scaling; turning; steering

1. Introduction

Bipedal locomotion has been studied extensively. In particular, how individuals scale their step size during cyclic walking and running has received prominent attention (Craik and Oatis 1995; Macellari, Giacomozzi, and Saggini 1999; Oberg, Karsznia, and Oberg 1993; Samson et al. 2001; Stolze et al. 2000). Relationships between step length, step frequency, progression speed, and anthropometry have also been investigated and compared for normal (Grieve and Gear 1966; Patla et al. 1991; Terrier and Schutz 2003) and pathological populations (Hausdorff 2005). Step placement has also been evaluated for acyclic movements, including turning while walking (Hase and Stein 1999; Orendurff et al. 2006) and gait initiation and termination (Breniere and Do 1991; Jian et al. 1993; Sparrow and Tirosh 2005; Winter 1995), particularly in the context of balance maintenance and postural control. Step scaling has received less attention in the context of functional tasks (e.g. lifting), although a small number of studies have investigated the coordination between stepping and grasping (Cockell, Carnahan, and McFadyen 1995; Marteniuk and Bertram 2001; van der Wel and Rosenbaum 2007).

Recent studies in our laboratory have classified the acyclic stepping patterns (transition behaviours) used during manual material handling (MMH) tasks (Wagner, Kirschweng, and Reed 2009) and developed predictive relationships for scaling those foot placements based on anthropometric, environmental and task parameters (Wagner, Reed, and Chaffin 2010). In these studies, a small number of transition behaviours were used by individuals to perform the majority of material handling transfers (e.g. pickup or delivery tasks preceded and followed by cyclic steps). Foot placements have been identified as a critical component to accurate biomechanical evaluation of postures adopted during lifting (Authier, Lortie, and Gagnon 1996; Bendix and Eid 1983; Plamondon et al. 2006; Wickel and Reiser 2008), an important component for accurate proactive design of industrial tasks (Chaffin, Andersson, and Martin 2006), and recent studies have focused on studying MMH tasks without foot movement constraints (Plamondon et al. 2010, 2012). Although our previous studies have begun to evaluate unconstrained stepping during pickup and delivery of MMH transfers for use with predictive human figure models (Reed and Wagner 2007), the analysis from those studies was limited to the steps immediately prior to and following when the load was lifted or deposited and did not investigate any potential effects of the position of the preceding cyclic steps. This limitation in our previous analysis implies that foot placements used to perform MMH transfer tasks are deterministic and independent of the previous step positions prior to the transfer. If this statement is accurate, individuals must be scaling

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their steps to accommodate or transition from cyclic walking (prior to the transfer) to facilitate their desired stepping strategy and foot placements. The study presented here is intended to evaluate the validity of this assumption, a potential limitation of our previous work, and identify any dependencies between step scaling and the stepping strategy used during unconstrained MMH transfers.

Previous research on the changes in step length during turning activities during cyclic walking may provide some insight into potential step-scaling strategies used during MMH. Using video analysis, Glaister et al. (2007) investigated turning behaviours during activities of daily living including walking through an office, parking lot, convenience store and a cafeteria. Turning steps were further classified as turn initiation, turn continuation, turn termination and adjustment steps. Turn continuation steps were identified as making up a sizeable portion of the total number of turn steps observed, suggesting that many of the observed turns occurred over multiple steps. Although they concluded that steps involved in turning activities make up a large portion of steps during activities of daily living, the observational focus of the study limits the applicability of those results to predictive-type models. In a study evaluating 180° rapid turns during cyclic walking, Hase and Stein (1999) identified the majority of participants alternated between two common strategies and related the selected strategy to the timing of the stimulus (with respect to the gait cycle) used to signal the participant to execute a turn. For most subjects, the turn was completed 'without resetting the underlying walking rhythm', suggesting that continuity of movement throughout the activity was important. Although the participant instructions to perform a quick/abrupt turn limit the direct applicability of the study to the more well-rehearsed turning observed in industrial settings, the alternation of observed turning strategies suggests a single deterministic approach to predicting step placements that is independent of previous cyclic step positions and may result in a simplified representation of the actual behaviours.

Studies that have investigated voluntary changes in direction (sometimes referred to as 'steering') have identified a temporal sequence of kinematic changes prior to whole body reorientation including changes in head and trunk orientation followed by medial–lateral deviation of the foot (Patla et al. 1991). In young adults, these changes occurred primarily within one stride prior to the turn event (Patla, Adkin, and Ballard 1999), suggesting that for voluntary changes in direction, individuals are planning for a turn several steps in advance of the turn execution. In evaluating the same parameters in older adults, Fuller, Adkin, and Vallis (2007) identified the same kinematic changes prior to a change in direction as young adults but observed older adults preferred to reorient their bodies along the new travel direction (40° change in direction) using two steps rather than one. Balance maintenance (or perceived balance maintenance) was found to be a critical component in turning strategy selection as older adults with lower reported levels of balance confidence were more likely to use the two-step turning strategy.

A small number of studies have investigated the coordination of prehension and locomotion. Cockell, Carnahan, and McFadyen (1995) investigated the relationship between stance limb and lifting hand during lifting from a laboratory experiment in which participants lifted an object while walking along a straight path alongside a table. The researchers observed an ipsilateral coordination strategy in which participants tended to stand on their left foot when lifting with their left hand and stand on their right foot when lifting with their right hand. van der Wel and Rosenbaum (2007) also evaluated the coordination of locomotion and prehension and conducted a study in which participants were asked to approach a table and move a bathroom plunger to a new horizontal location on the table. The approach distance to the table was varied to facilitate one to four steps prior to grasping of the plunger. The results indicated that participants preferred to support their body with the leg contralateral to the direction of the instructed transfer. The researchers also showed that for longer starting distances from the table, the participants were better able to plan their foot placements to facilitate their preferred strategy. Interestingly, participants exclusively chose to vary their stride lengths and not initial step (i.e. left or right), which was not controlled by the experimenters. Although the study provides further understanding into the underlying motor control strategies used by participants when approaching and lifting an object, the applicability to predictive models used for ergonomics assessment, in which the position of the foot with respect to the load must be simulated, is limited.

Without a better understanding of how individuals transition from cyclic stepping to an MMH transition, the application of much of the previous research concerning foot placements used during MMH is limited to the independent analysis of consecutive work tasks. Job evaluation techniques based on such a division of labour include time study techniques (Taylor 1911), motion study techniques (Gilbreth and Gilbreth 1917) and methods-time measurement (Maynard, Stegemerten, and Schwab 1948), and have been applied to ergonomics analysis of manual work as a basis for improving workplace layout (Colombini 1998; Karhu, Kansi, and Kuorinka 1977). However, because of the complex nature and progression of musculoskeletal disorders, this classical approach to job analysis may have limited usefulness for effectively assessing and preventing musculoskeletal disorders (Dempsey and Mathiassen 2006), suggesting that a more holistic evaluation of a manual material handler's job may be required. Several simulation-based frameworks in which virtual environments and digital representations of human figures are used for prospective biomechanical and ergonomics evaluation have been proposed (e.g. Badler et al. 2005; Raschke, Kuhlmann, and Hollick 2005; Reed et al. 2006) that could be used to directly evaluate those risk factors. However, the accuracy of those models is dependent on the truthful simulation of postures and motions, which intrinsically depend on an accurate understanding and representation of the foot placements used throughout the job cycle.

The objective of the current study is to characterise how individuals scale their steps prior to MMH transfer tasks. A laboratory study was conducted wherein the distance travelled prior to delivering an object was varied. The data were compared to three idealised step-scaling behaviours. We assessed whether the stepping strategies used to facilitate a manual handling transfer were dependent upon previous cyclic steps.

2. Methods

Participants moved a two-handed box with cylindrical handles between pickup and delivery locations while their whole body motions were recorded. Participants lifted and delivered the objects from shelves set to 53% of stature above the ground (approximately waist height). The participant start location, pickup shelf position and included angle between the pickup and delivery shelves were fixed throughout all the trials. The position between the pickup and delivery locations was varied to six evenly spaced distances (Figure 1) selected for each participant based on their stride length. Four participants performed additional transfers totalling 12 evenly spaced distances between the pickup and delivery locations. Test conditions were selected to be similar to previously observed MMH tasks in an automotive assembly plant (Wagner, Kirschweng, and Reed 2009). The data were collected as part of a larger MMH laboratory experiment (see Wagner, Reed, and Chaffin [2010] for a complete description). Figure 1 depicts the transfer trial conditions for the six evenly spaced delivery distances.

2.1. Subjects

Subjects were recruited by word of mouth and solicited via public posting. Subjects were right-handed and had no reported history of musculoskeletal disorders or recurring low back pain. Participants did not have special experience working in a manual material handling capacity.

Data were obtained from 10 male and 10 female paid participants: mean (SD): age: 20.7 (1.3) years and 23.9 (5.3) years; stature: 181.1 (9.3) cm and 167.5 (6.8) cm; body mass index (BMI): 25.4 (4.1) kg/m^2 and 21.6 (2.6) kg/m^2. The protocol was approved by an institutional review board, and all participants provided written, informed consent.

2.2. Facilities

A six-camera Qualisys Proreflex 240-MCU passive optical motion tracking system (Qualisys, Sweden) was used to capture kinematic data at 50 Hz within a 3.6 $\times$ 4.8 m floor area. 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. Pressure switches on the pickup and delivery shelves were used to determine the time of pickup and delivery. All analogue signals were sampled at 500 Hz.

Twenty-nine 25-mm-diameter retro-reflective markers were affixed to each participant to track whole body motion. A combination of bony landmarks, measured anthropometry and marker positions was used to calculate foot position and orientation. Markers placed on the lateral most protrusion of the fifth metatarsal head, the medial most protrusion of the first metatarsal head and the lateral malleolus were used to create a local coordinate reference frame for each foot. The distance

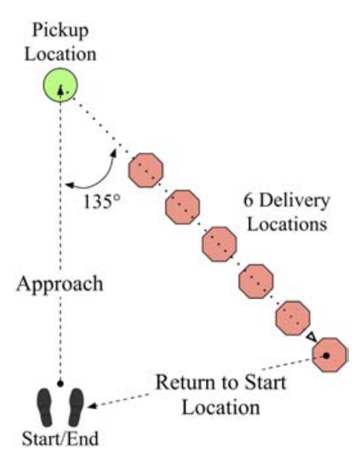

Figure 1. Graphical depiction of the six delivery trials.

between the lateral and medial malleoli was measured and used to define the offset distance from the lateral malleolus marker to estimate the heel joint centre. The foot position projected to the ground plane was calculated as the mid-point between the lateral and medial foot markers located on the distal aspect of the foot.

2.3. Test conditions

Participants approached the object on a shelf from three to four steps away, picked up the object, transferred it to another shelf (delivery location) and returned to the initial start position. The stance of a participant prior to delivering the box for 12 unique delivery distances is shown in Figure 2. The box had horizontal cylindrical handles with diameters of 3.81 cm located 29.5 cm apart and had a total mass of 4.54 kg. The presentation of trials was randomised for each participant.

2.4. Procedures

The data collection was part of a larger MMH experiment described in detail by Wagner, Reed, and Chaffin (2010). In summary, participants attended two data collection sessions, on different days. During the first session, participants were introduced to the equipment being used, had their anthropometry recorded and practised the load transfer protocol to be used during the second session. During the load transfer practice, which lasted approximately 90 min, the participants became familiar with each condition and were specifically instructed that the weight and configuration of the loads they handled would be the same during the next session. Furthermore, the participants were informed that at no time during the experiment would the load weights be changed.

During the single practice load transfer session, the delivery distance was varied to identify the shelf locations that corresponded with participants transitioning from using zero through five steps to complete the transfer of the two-handed

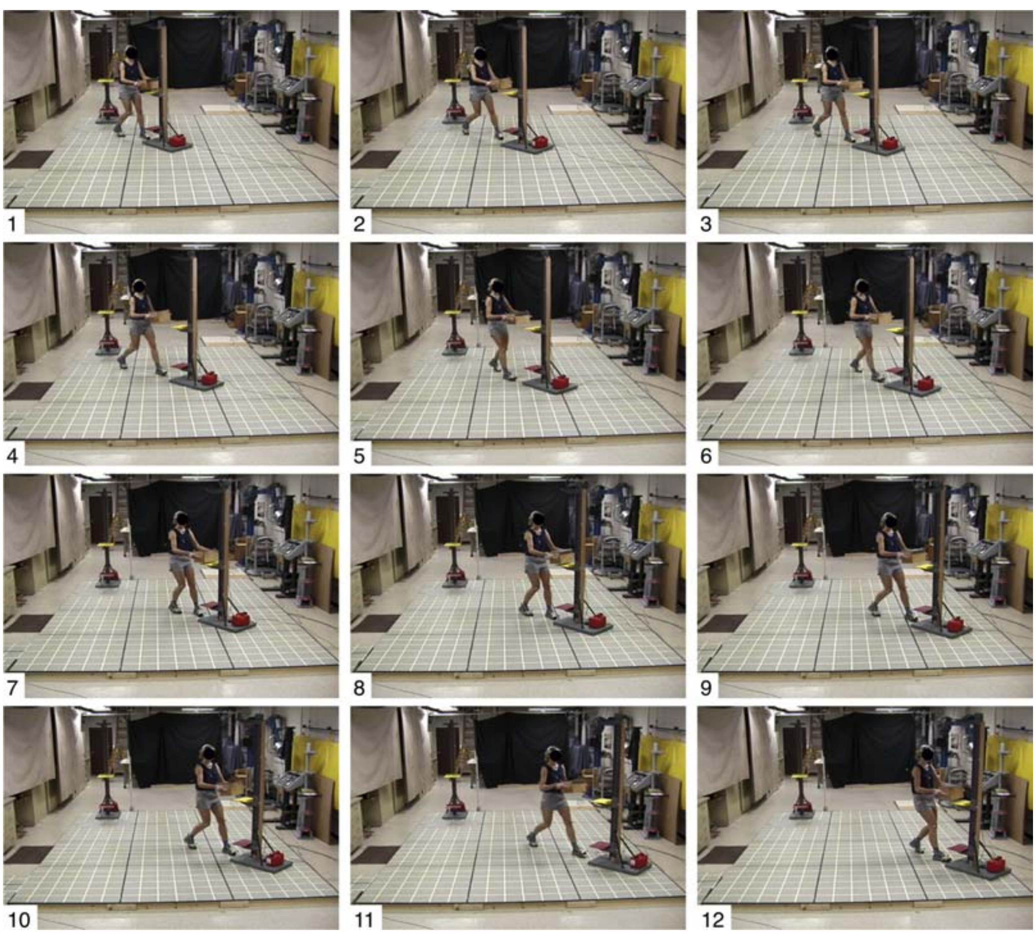

Figure 2. Participant in the double support phase prior to the terminal stance (i.e. when the load is delivered) for 12 evenly spaced delivery distance conditions ('1' is the shortest and '12' is longest delivery distance).

load between the pickup and delivery location. First, the distance from the object at which the participant preferred to stand to pick up the object was determined (zero-step distance). Second, the distance at which the participant reliably used five steps to reach the pickup location was determined (five-step distance). Third, trials were conducted to determine five evenly spaced distances between the zero- and five-step distances to verify that behaviours with zero through five steps, inclusive, were observed. The number of repeated trials performed by each participant during this determination varied between participants. Trials were repeated until a consistent number of steps associated with each distance were observed. Using participant-specific distances resulted in participants with different normal stride lengths using the same number of steps. These distances were used to set the approach and delivery distances for the second session. As part of the practice sessions, each participant's nominal step length, defined as the mean step length in normal walking while carrying the two-handed load, was determined. 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 (e.g. activities of rock climbing and long-distance running were given).

Data for each MMH transfer trial were collected for 12 s, although the pace of each transfer was self-selected. 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 allowed to practise the transfer prior to data collection if they requested. A light emitting diode (LED) light placed near the pickup tower was used to signal the participant 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 signalled the trial was completed. Trials in which the subject did not return to the correct start location were discarded and the test condition was repeated.

2.5. *Data analysis and step parameterisation*

The pattern of foot motions used in each delivery (delivery transition behaviour) was classified using the Lexical Transition Classification System (L-TRACS) method as defined in Wagner, Kirschweng, and Reed (2009). L-TRACS defines a descriptive representation of the transition behaviour, which provides a consistent vocabulary for MMH stepping patterns. Individual steps are characterised with respect to the turn direction following the MMH manipulation to account for symmetry. For example, for a delivery in which an individual approaches a position, delivers an object, turns to the right and walks to the next task, the right foot (or step) is defined as the ipsilateral limb (i.e. same side the direction of turn) and the left foot is defined as the contralateral limb. The relationship between transition behaviour and step scaling was evaluated.

The Quantitative Transition Classification System (Q-TRACS) previously described by Wagner, Reed, and Chaffin (2010) was used to parameterise each step allowing for the description of cyclical and acyclical stepping motions. In summary, each step is defined using eight parameters that include the location of the foot origin, the orientation of the foot, the times of the heel contact, toe contact, heel lift and toe lift events.

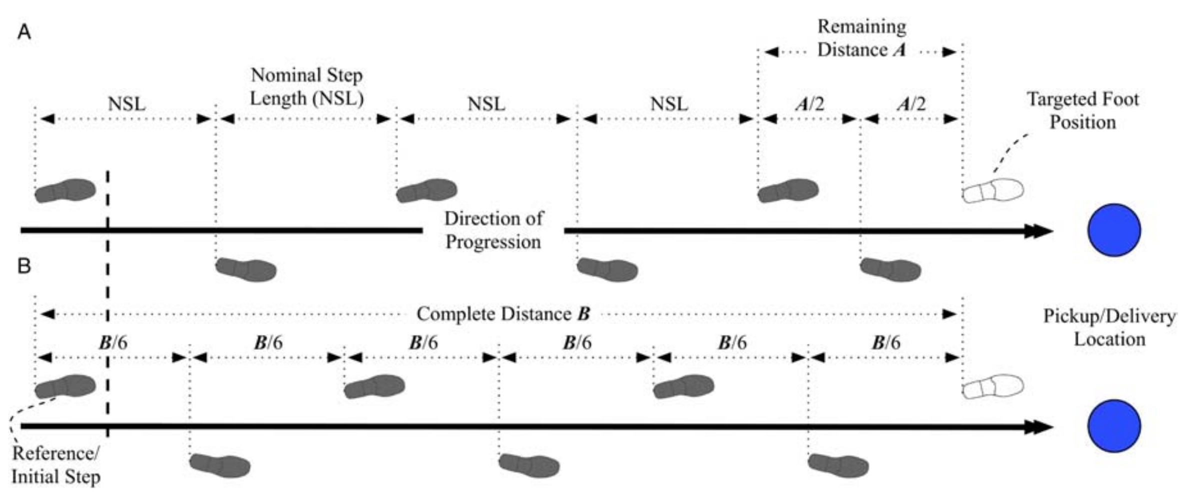

Figure 3. Two idealised step scaling strategies depicting (A) finite step scaling with scalable steps defined at two and (B) universal step scaling. Both strategies facilitate landing on a specific foot target (depicted here as the white outlined step prior to the pickup/delivery location).

2.6. Idealised step scaling strategies

To guide the interpretation of the results from the laboratory experiment, three idealised strategies for scaling the steps prior to the execution of the transfer task (i.e. delivery of the box) are proposed:

(1) Universal step scaling (Figure 3B), in which all the steps in a sequence are equivalently scaled to a fraction of the nominal step length such that the final step position with respect to the load is realised.
(2) Finite step scaling (Figure 3A), a similar strategy to universal step scaling, except that a maximum number of N steps preceding the final step location are allowed to be scaled.
(3) Flexible step scaling, a hybrid strategy combining the aspects of finite step scaling with that of the flexibility to also change the terminal stance (i.e. transition behaviour).

Variations on the universal and finite scaling approaches are possible. For example, Figure 3(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 finite 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 finite and universal scaling techniques assume the terminal stance (or lead foot position relative to the load) is invariant.

In the current experiment, only a change in the distance the participant travelled to deliver the load was varied between trials. Participants that use the same stepping strategy at the delivery location to deliver the load and change directions for all distances tested must be scaling their steps prior to the delivery (e.g. universal or finite step scaling) to maintain the same lead configuration, regardless of delivery distance. In contrast, participants that change stepping strategies (e.g. change their lead foot configuration) and did not maintain a consistent lead foot position throughout the trials will be identified as using a different stepping strategy (e.g. flexible step scaling). The idealised strategies will be used to qualitatively evaluate the step-scaling strategy of each participant.

3. Results

3.1. Distribution of delivery transition behaviours

Results from 135 delivery transition behaviours are presented (9 trials were excluded due to motion capture marker occlusion). The distribution of the five most commonly observed delivery transition behaviours observed is depicted in Figure 4. The most commonly observed transition behaviour (*one-step contralateral lead foot*) was also observed as the

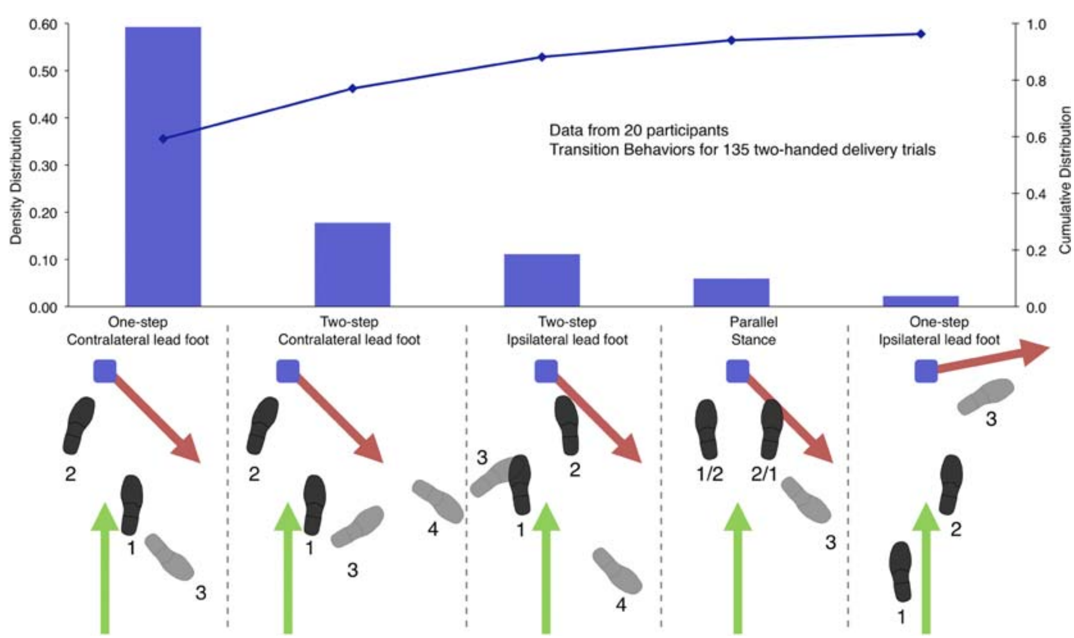

Figure 4. Absolute and cumulative distributions of the five most frequently used transition behaviours for all subjects. The five depicted behaviours accounted for 96% of all behaviours observed.

most frequently used behaviour in a previous automotive plant study (Wagner, Kirschweng, and Reed 2009). The five most frequently observed behaviours accounted for 96% of all the transitions observed. All participants used more than one transition behaviour across the delivery distances tested. The majority of transition behaviours were accomplished with a split stance during the delivery with the contralateral foot positioned as the lead foot. Contralateral and ipsilateral lead foot delivery transitions accounted for 78% and 16% of the observed transitions, respectively.

Table 1 depicts the terminal stance lead foot for all the participants for the delivery trials depicted in Figure 1. Of the 20 participants observed, 2 performed the delivery transfer with the same lead foot (contralateral) for all the delivery distance conditions. Four participants used a combination of contralateral lead foot and parallel stance transition behaviours, while the remaining 14 participants used a flexible step-scaling strategy in which both ipsilateral and contralateral lead foot transition behaviours were observed. Of the 11 participants who used a flexible step-scaling strategy and had data collected at and between the third and fourth defined delivery distances (depicted in Figure 1), 10 participants used a different terminal stance between those transfer distances. The remaining participant used an ipsilateral lead foot strategy for both transitions.

3.2. Step scaling

Representative data from a participant utilising the most common transition behaviour for 12 delivery distances, aligned to the first step following when the box was initially lifted, are depicted in Figure 5. The participant completed the 12 deliveries using between 3 and 6 steps (including the first step following pickup and the final step prior to delivery). Delivery distances utilising three and five steps correspond to contralateral lead foot transitions, while trials utilising four and six steps correspond to ipsilateral lead foot transitions.

The range of observed mean step length varied from 503 to 741 mm with a mean value of 646 mm for all participants. Stature alone explained 12% of the observed variance in mean participant step length using a linear regression. The mean step length scaled by stature across all participants was 0.37. Table 2 lists the mean and range of step lengths grouped for each step prior to delivery, as a fraction of the nominal step length while carrying the two-handed load, for the participant depicted in Figure 5 and for all participants grouped together. Both the participant depicted in Figure 5 and the grouped step length data for all the participants showed an increase in step length variability as the distance to the delivery location

Table 1. Terminal stance lead foot (C – contralateral, I – ipsilateral, P – parallel, ND – no data) for all the participants for the six prescribed delivery transfer distances.

Participant number[a]	Distance 1 (shortest)	Distance 2	Distance 3	Distance 4	Distance 5	Distance 6 (longest)
1[b]	C	C	I	C	C	I
3[b]	ND	ND	ND	C	ND	I
4[b,c]	C	C	C	C	C	C
5[b]	C	C	P	C	C	C
6	C	C	P	C	C	I
7	C	C	C	C	C	C
8	C	C	I	C	C	C
9	C	C	I	C	C	I
10	C	C	I	C	C	C
11	C	C	C	ND	C	I
12	C	C	I	C	C	I
13	C	C	I	C	C	I
14	I	C	I	I	C	C
15	C	C	I	C	C	P
16	C	C	C	C	C	C
17	C	C	I	C	C	C
18	C	C	I	C	C	C
19	C	C	C	C	P	C
21	C	C	P	C	C	C
27	C	P	C	C	C	C

[a] Particpant numbering is presented to be consistent with data collected as part of a larger study (Wagner, Reed, and Chaffin 2010).
[b] These 4 participants performed an additional 6 delivery transfers for a total of 12 unique distances tested. The data for the intermediate distances are not shown here but are included in the text.
[c] An ipsilateral transition behaviour was observed for this participant for an intermediate distance not depicted here.

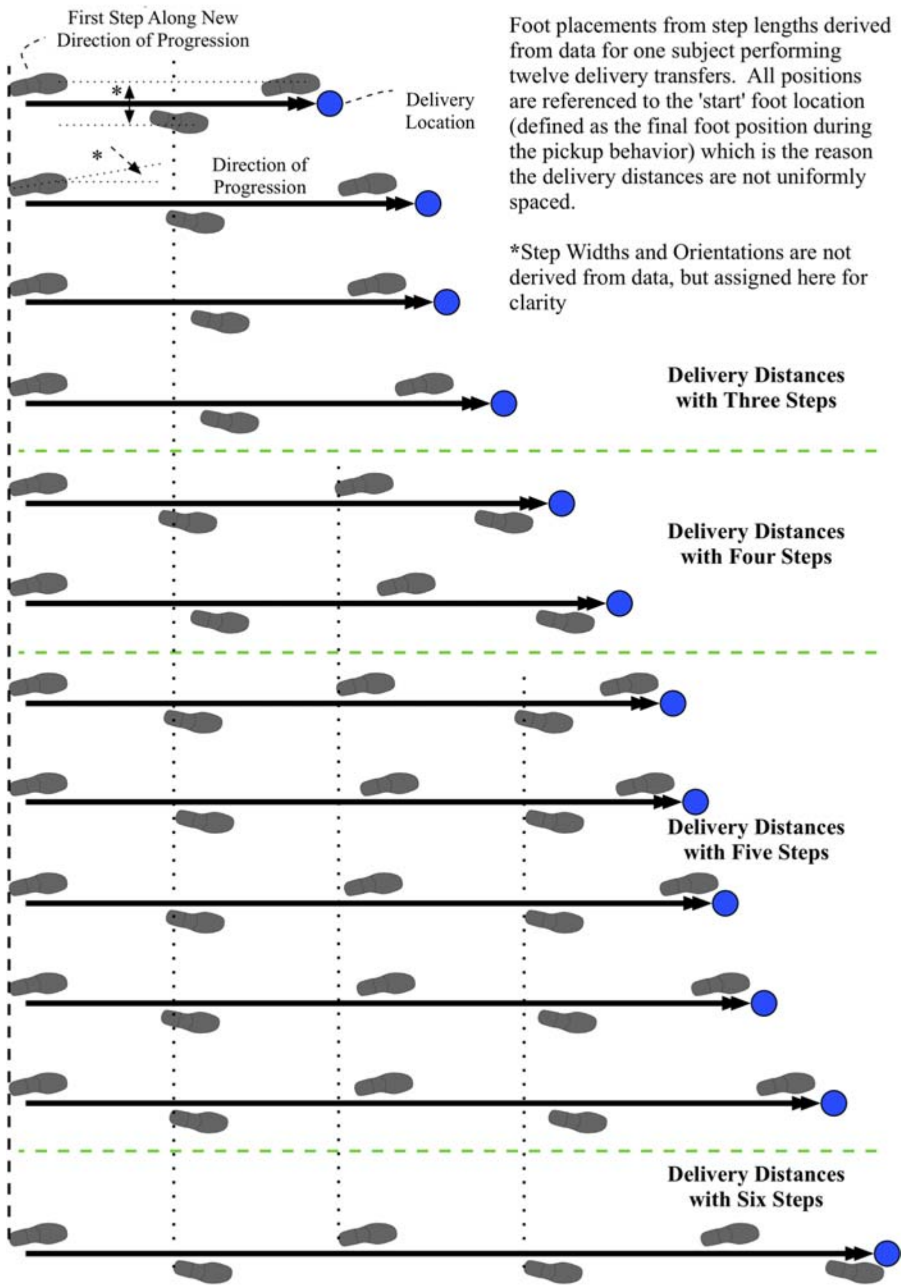

Figure 5. Foot placements depicting the step lengths of a participant with representative data performing 12 transfer trials in which the delivery distance was varied.

decreased. The maximum differences in normalised step length for each participant for the four steps prior to delivery were calculated. The average of those differences for all the participants increased from the fourth, third, second and first step prior to delivery from 0.15, 0.22, 0.39 and 0.67, respectively.

The majority (90%) of participants were observed to change terminal stance across different delivery distances. Figure 6 depicts data from participants who used three different scaling strategies. Figure 6(A) depicts data from a participant who utilised transition behaviours with a contralateral lead foot and ipsilateral lead foot. Figure 6(B) depicts data from a participant who utilised transition behaviours with a contralateral lead foot and a parallel stance. The difference in transition behaviour preference is illustrated in Figure 6(A) and (B). The third and fourth rows in Figure 6(A) depict a change in behaviour from an ipsilateral to contralateral lead foot strategy in which the step length prior to delivery between the two trials is approximately equivalent. The fourth and fifth rows of Figure 6(B) depict a similar consistent step length prior to

Table 2. Summary statistics for step lengths (normalised to nominal two-handed carrying step length) grouped by the step number prior to delivery. Data for a single representative subject and for all subjects grouped.

Step length summary statistics (fraction of nominal step length)	Steps prior to delivery				
	5[b]	4	3	2	1
Mean ± standard deviation (single subject[a])	1.03 ± 0	1.00 ± 0.04	1.12 ± 0.09[c]	1.10 ± 0.09[c]	0.91 ± 0.24
Largest step length (single subject)	1.03	1.05	1.23	1.22	1.31
Smallest step length (single subject)	1.03	0.96	0.94	0.88	0.54
Mean ± standard deviation (all subjects)	1.04 ± 0.06[c]	1.02 ± 0.09	1.05 ± 0.15[c]	1.00 ± 0.16	0.82 ± 0.25[c]
Largest step length (all subjects)	1.16	1.34	1.43	1.38	1.37
Smallest step length (all subjects)	0.92	0.66	0.62	0.58	0.20

[a] Nominal step length for single subject data was 685 mm.
[b] Data available only for 14 participants in the 5th step column as 6 participants used only a maximum of 4 steps prior to delivery.
[c] Mean step length is statistically different (*t*-test, $p < 0.05$) from the normalised two-handed carrying step length of 1.

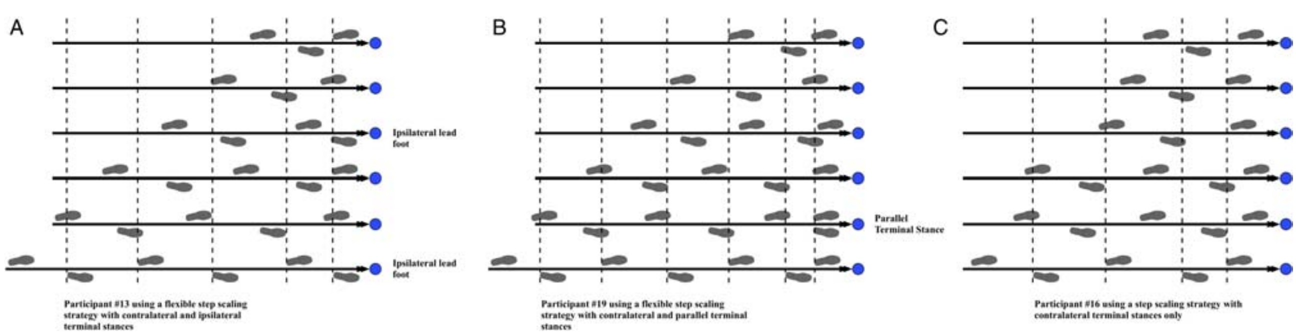

Figure 6. Step lengths for three participants performing six delivery tasks that depict (A) a flexible step-scaling strategy with contralateral and ipsilateral lead foot behaviours, (B) a flexible step-scaling strategy with contralateral lead foot and parallel stance behaviours, and (C) a step-scaling strategy with a consistent contralateral lead foot strategy.

delivery but with a change in transition behaviour from a contralateral lead foot behaviour to one with a parallel stance. Figure 6(C) depicts data from a participant who used only transition behaviours with a contralateral lead foot terminal stance. The step lengths observed in Figure 6(C) ranged from 0.6 to 1.33 (scaled to nominal step length). In contrast, the step lengths observed in Figure 6(A) and (B) ranged from 0.57 to 1.22 and 0.34 to 1.2, respectively.

4. Discussion

A theoretical framework of idealised step-scaling strategies was introduced to compare with the experimental data. The majority of observed transfers were accomplished with a split stance contralateral lead foot transition behaviour with all but one participant utilising that terminal stance in over half their transfers. The majority of participants utilised a flexible step-scaling strategy in which both the step lengths prior to delivery and the transition behaviour were varied to accomplish the delivery transfers over different distances. Stature was a poor predictor of the mean step lengths prior to delivery, suggesting that the observed scaling strategies resulted from more than anthropometric differences. The mean step length for steps prior to delivery was always equal to or larger than the nominal step length (calculated for each participant) except for the step immediately prior the delivery transfer, which was significantly shorter than the nominal step length and was observed to have the largest variance. The data suggests that individuals are scaling their last step to target a position with respect to the load and prefer a shorter step immediately before the load is delivered. Although it appears the previous steps are scaled to facilitate a contralateral lead foot transition behaviour, the criteria that are used by an individual to switch to a different transition behaviour requires further research.

Although most participants seemed to scale their steps (prior to the transition) to facilitate a transfer with a single behaviour or terminal stance, the majority of participants did adopt different transition behaviours to accommodate the location of the transfer with respect to the gait cycle (or cyclic steps prior to the transition). The contralateral terminal stance preference observed in the current study is consistent with a previous observational study of workers performing MMH tasks in an automotive assembly plant that identified 71% of the observed transition behaviours were performed using a split stance strategy with the majority of those transitions being performed with a contralateral lead foot transition behaviour (Wagner, Kirschweng, and Reed 2009). This similarity suggests both groups scaled their foot placements to facilitate similar transition behaviours in spite of differences in MMH experience, task requirements and setting.

Previous work that has focused on turning during walking may provide some insight into the transition behaviour preference observed in this study. In evaluating the kinematics of a 180° turn, Meinhart-Shibata et al. (2005) had subjects pick up a light weight bowl with two hands to approximate self-selected turning behaviours that would be used in a kitchen-type setting. Treating the delivery transfers observed in the current study in a similar manner, the steps used to facilitate the turn during the delivery task could be compared to the steps used to facilitate turning during walking. In this context, the use of two transition behaviours (and preference for one) with opposing terminal stances used by the majority of participants in the current study may be similar to the use of the 'step' and 'spin' turn strategies that have been described for changing direction during cyclic walking along a straight path (Hase and Stein 1999; Taylor, Dabnichki, and Strike 2005; Taylor, Strike, and Dabnichki 2006). Hase and Stein (1999, p. 2914) described the two turning strategies with the following examples:

> ... to turn to the right when the right foot was placed in front, subjects generally altered direction by spinning the body around the right foot (spin turn). To turn left when the right foot was in front, subjects shifted weight to the right leg, externally rotated the left hip, stepped onto the left leg, and continued turning until the right leg stepped in the new direction (step turn).

The step turn strategy described by Hase and Stein (1999) is similar to the one-step and two-step contralateral lead foot transition behaviours (Figure 4) described in this study. Taylor, Dabnichki, and Strike (2005) also identified two types of spin turn sub-strategies as the 'ipsilateral crossover' and 'ipsilateral pivot', which are similar to the one-step ipsilateral lead foot transition and two-step ipsilateral lead foot transition, respectively, described here. The similarity in self-selected transition behaviours and previously reported self-selected turning strategies suggests that turning and the foot positions associated with changing the orientation of the body are a critical component to better understanding how individuals scale their steps to facilitate an MMH transfer task.

In the study conducted by Hase and Stein (1999), participants were instructed to walk in a straight line and turn 180° and proceed back to the starting location immediately after receiving an electrical stimulus. The timing of the stimulus was varied to different instances in the gait cycle. Similar to the results found here, the majority of participants utilised both step (contralateral lead foot) and spin (ipsilateral lead foot) turning strategies with a minority of participants solely using the step turn strategy to accomplish the turn. Although the exact reasons why a minority of participants exclusively used the step turn strategy could not be determined, walking speed was ruled out as a major contributing factor as both groups walked with similar gait speeds. Hase and Stein (1999) did observe that the selection of turning strategy was '... determined by which leg was placed in front for braking', which is consistent with the data presented in this study regarding the terminal stance prior to the delivery event.

If no step scaling occurred prior to the final step, the observation by Hase and Stein (1999) would suggest an even distribution of ipsilateral and contralateral terminal stance behaviours (assuming a split stance strategy is used exclusively) to be used as the delivery distance was varied. Step scaling prior to a lifting transfer was similarly observed by van der Wel and Rosenbaum (2007) for an approach and single-handed transfer task. Reasons for the preference of contralateral lead foot (step) turning strategy may include greater stability and more stable base of support (Hase and Stein 1999; Patla et al. 1991; Taylor, Dabnichki, and Strike 2005) and requiring a range of motion and moments out of the sagittal plane no more demanding than walking along a straight path (Taylor, Dabnichki, and Strike 2005). In contrast, the ipsilateral lead foot (spin) strategy requires increased coordination, range of motion out of the sagittal plane and muscular demand (Taylor, Dabnichki, and Strike 2005), increased push-off power from the soleus (Hase and Stein 1999), and uses a 'fall' into the new direction of progression (ipsilateral cross-over) in which the centre of gravity is outside the base of support during the turning motion (Taylor, Strike, and Dabnichki 2006). The two-step ipsilateral lead foot transition behaviour observed in this study did not have a corresponding commonly observed turning strategy, suggesting that while the behaviour may be suitable to accomplish a planned MMH transfer, it is not sufficiently preferred to have been previously reported when participants are instructed to perform a quick/abrupt turn while walking. The prevalence of the two-step ipsilateral lead foot transition as the third most observed behaviour may be explained by its similarity to the one- and two-step contralateral lead foot behaviours with respect to stability and base of support, suggesting that those components are important factors when selecting foot positions. However, the two-step ipsilateral lead foot transition requires an additional pivot step (not along the new direction of progression), increasing time to reorient the body to the new direction of progression, which may be one reason why this strategy is not as prevalent as the contralateral lead foot strategies, which do not have such a limitation.

Our previous work suggests that participants are targeting the lead foot position, with respect to the position of the transfer location, when using a split stance transition behaviour (Wagner, Reed, and Chaffin 2010). A similar result was observed by Sparrow et al. (2003) for the foot positions during an approach and grasping task. The data presented here suggest that to accommodate the targeted lead foot position, participants use a flexible step-scaling strategy and have allowed several steps prior to the terminal stance lead foot to be scaled. The step length prior to the placement of the lead foot was allowed to vary the most with a standard deviation of 25% of the nominal step length for each participant being observed. The three step lengths prior to the placement of the lead foot all had standard deviations greater than 10% of the nominal step length determined for each participant. Patla et al. (1991) observed participants needed to be signalled at least one step prior to a turn for participants to successfully perform a quick/abrupt change in direction on the next step, suggesting a minimum amount of necessary planning to facilitate an MMH transfer. Similarly, Xu, Carlton, and Rosengren (2004) observed that anticipatory postural changes of the centre of mass and centre of pressure occurred as early as the heel strike of the step prior to a turn following unconstrained walking. However, participants in their study were instructed to not adjust their stride length, and the question of how adjustments in stride interact with the type of anticipatory postural adjustments remained a topic of future research. Fuller, Adkin, and Vallis (2007) observed that in voluntary turning of an older population segmental changes (i.e. head reorientation, trunk reorientation, etc.) occurred over two or more steps prior to travel along the new direction 69% of the time and over one step 31% of the time, suggesting that during well-planned turning motions, kinematic changes to nominal walking occur several steps prior to the actual turn. Although the data presented here clearly show step length variations (which increased as participants moved closer to the delivery location), additional research is necessary to fully define the relationship between maximum number of scalable steps and amount of step scaling within those steps that participants are willing to perform prior to changing to a different transition behaviour. All the study participants were determined to be right-handed; left-handed workers might exhibit behaviours different from right-handed workers when performing the tasks in this study.

A potential limitation of this study is that the foot placements used by participants to pick up the box during the transfer task were unconstrained (i.e. participants were not required to pick up the box using a specific stepping strategy). Although the delivery location was varied uniformly along a straight vector, differences in foot placements at the pickup location resulted in non-uniform delivery distances (when defined as the distance between the first foot placement following pickup and the delivery location; see Figure 5 for illustration). The non-uniformity in delivery locations confounds the direct comparisons between delivery distance trials, even though the delivery distances were scaled to each participant's nominal step length while carrying the box. Of potentially greater concern is that the non-uniform differences in delivery distance could result in distances in which only one transition behaviour is preferred and a delivery distance range that would cause an ipsilateral lead foot strategy, for example, would not be evaluated. The same concern could also result from the delivery distance spacing being too large in which a transition to another behaviour would occur between the tested distances. This could potentially explain why 2 of the 20 participants were observed to only use contralateral lead foot transition behaviours. However, in the study by Hase and Stein (1999) that analysed turning strategies during walking, a minority of participants were similarly observed to solely use a single contralateral lead foot strategy.

Another limitation of the study is that delivery distance was proportionally correlated to the included turn angle at the delivery transfer location. Participants were instructed to return to the start location following the delivery of the box. As the start location was fixed, longer delivery distances resulted in larger turn angles between the approach and departure directions prior to and following the delivery, respectively. This limitation may confound the results presented here, as turn angle has been associated with foot placement position during MMH transfer tasks (Wagner, Reed, and Chaffin 2010). However, a change in transition behaviour due to an increase in turn angle will most likely manifest as an increase in the number of steps (i.e. one-step versus two-step contralateral lead foot behaviour) and not a change in the terminal stance. For the majority of participants observed here, a transition from a contralateral to ipsilateral lead foot terminal stance occurred between the second and third delivery distance and then back to a contralateral lead foot terminal stance for longer delivery distances. As turn angle increased linearly with delivery distance, the multiple transitions between contralateral and ipsilateral terminal stance lead foot suggest any confounding effect with terminal stance to be small.

Other limitations of this study include that only a single transfer task (i.e. two-handed box, single weight, single delivery height) was analysed, that the longest delivery distance tested was accomplished in 4–5 steps by the majority of participants, and that the subject population did not have substantial previous experience performing manual material handling tasks. The task conditions were selected to facilitate a reasonable set of experimental trials based on task conditions observed from a previous study (Wagner, Kirschweng, and Reed 2009). Although our previous research showed that object weights exceeding 4 kg were uncommon, tasks with relatively heavy objects are more likely to be the subject of ergonomic inquiry. Hence, the object mass was chosen to be 4.5 kg, which lies at the upper end of the range observed in industry. Our previous survey of worker motions in an industry plant showed a range of approach and departure angles, with acute angles being observed more frequently than those greater than 90°. In pilot testing for the current laboratory project, acute angles were associated with greater variability in transition stepping behaviours. Consequently, to focus the current work on step scaling, a turn angle of 135° was used. Re-examination of data from our earlier field study of workers in an assembly plant showed that although the average height from which objects were lifted was above 1 m from the floor, heavier objects were often lifted from lower positions. Pilot investigations showed that the height chosen for the current study allowed the subjects to grasp and lift the relatively heavy object repeatedly without apparent difficulty. The generalisation of these results is limited by the test conditions. In particular, changes in the object mass, the height from the ground or the turn angle could alter the behaviours observed. For example, a particularly heavy load may necessitate an individual to keep the load as close to the body as possible, requiring the use of a parallel stance during lift or delivery (Bendix and Eid 1983; Chaffin et al. 1986). However, five transition behaviours, of which four were repeatedly used by the participants in this study, accounted for over 90% of the observed transitions performed by experienced manual material handlers in an automotive assembly plant (Wagner, Kirschweng, and Reed 2009). This suggests that the transitions performed by the participants in this study were similar to those used by experienced manual material handlers in an industry setting. More research is needed to create a model that can be generalised to a large range of industrial tasks.

The number of steps prior to the delivery was limited by the available experimental set-up. Baril-Gingras and Lortie (1995), in a study evaluating the handling techniques of workers in a large transport company, reported that workers walked in 57% of the material handlings observed. A distribution of the number of steps to accomplish each transfer was not reported, but the large percentage of transfers with a walking component may be overestimated given their definition of walking as transfers that required two or more steps. For the longest delivery distances tested in the study presented, it is possible the participants did not achieve a steady state cyclic gait prior to beginning their step scaling to facilitate the delivery transition behaviour, making the exact determination of the transition between walking and step scaling difficult. The standard deviation of the normalised step lengths for all the participants was observed to decrease as the number of steps prior to the delivery event increased, suggesting that more step scaling occurred as the participant approached the delivery location. However, the variation of all the steps (prior to the delivery event) was greater than the largest coefficient of variation of 3.7% reported for step length of preferred walking speed in a study that evaluated the variability of unconstrained walking (Terrier and Schutz 2003), suggesting that either walking with a load is inherently more variable than unconstrained walking or, more likely, steady state walking was not achieved by all the participants.

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Note

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References

Authier, M., M. Lortie, and M. Gagnon. 1996. "Manual Handling Techniques: Comparing Novices and Experts." *International Journal of Industrial Ergonomics* 17 (5): 419–429.

Badler, N. I., J. Allbeck, S.-J. Lee, R. Rabbitz, T. Broderick, and K. Mulkern. 2005. *New Behavioral Paradigms for Virtual Human Nodels*, Technical Paper 2005-01-2689, Warrendale, PA: SAE International.

Baril-Gingras, G., and M. Lortie. 1995. "The Handling of Objects Other Than Boxes: Univariate Analysis of Handling Techniques in a Large Transport Company." *Ergonomics* 38 (5): 905–925.

Bendix, T., and S. E. Eid. 1983. "The Distance between the Load and the Body with Three Bi-Manual Lifting Techniques." *Applied Ergonomics* 14 (3): 185–192.

Breniere, Y., and M. C. Do. 1991. "Control of Gait Initiation." *Journal of Motor Behavior* 23 (4): 235–240.

Chaffin, D. B., L. S. Gallay, C. B. Woolley, and S. R. Kuciemba. 1986. "An Evaluation of the Effect of a Training Program on Worker Lifting Postures." *International Journal of Industrial Ergonomics* 1 (2): 127–136.

Chaffin, D. B., G. Andersson, and B. J. Martin. 2006. *Occupational Biomechanics*. 4th ed Hoboken, NJ: Wiley-Interscience.

Cockell, D. L., H. Carnahan, and B. J. McFadyen. 1995. "A Preliminary Analysis of the Coordination of Reaching, Grasping, and Walking." *Perceptual and Motor Skills* 81 (2): 515–519.

Colombini, D. 1998. "An Observational Method for Classifying Exposure to Repetitive Movements of the Upper Limbs." *Ergonomics* 41 (9): 1261–1289.

Craik, R., and C. A. Oatis. 1995. *Gait Analysis: Theory and Application*. 1st ed St. Louis, MO: Mosby.

Dempsey, P. G., and S. E. Mathiassen. 2006. "On the Evolution of Task-Based Analysis of Manual Materials Handling, and Its Applicability in Contemporary Ergonomics." *Applied Ergonomics* 37 (1): 33–43.

Fuller, J., A. Adkin, and L. Vallis. 2007. "Strategies Used by Older Adults to Change Travel Direction." *Gait Posture* 25 (3): 393–400.

Gilbreth, F. B., and L. M. Gilbreth. 1917. *Applied Motion Study*. New York: Sturgis & Walton.

Glaister, B. C., G. C. Bernatz, G. K. Klute, and M. S. Orendurff. 2007. “Video Task Analysis of Turning during Activities of Daily Living.” *Gait Posture* 25 (2): 289–294.
Grieve, D. W., and R. J. Gear. 1966. “The Relationships between Length of Stride, Step Frequency, Time of Swing and Speed of Walking for Children and Adults.” *Ergonomics* 9 (5): 379–399.
Hase, K., and R. B. Stein. 1999. “Turning Strategies during Human Walking.” *Journal of Neurophysiology* 81 (6): 2914–2922.
Hausdorff, J. M. 2005. “Gait Variability: Methods, Modeling and Meaning.” *Journal of Neuroengineering and Rehabilitation* 2: 19.
Jian, Y., D. Winter, M. Ishac, and L. Gilchrist. 1993. “Trajectory of the Body COG and COP during Initiation and Termination of Gait.” *Gait and Posture* 1 (1): 9–22.
Karhu, O., P. Kansi, and I. Kuorinka. 1977. “Correcting Working Postures in Industry: A Practical Method for Analysis.” *Applied Ergonomics* 8 (4): 199–201.
Macellari, V., C. Giacomozzi, and R. Saggini. 1999. “Spatial-Temporal Parameters of Gait: Reference Data and a Statistical Method for Normality Assessment.” *Gait Posture* 10 (2): 171–181.
Marteniuk, R. G., and C. P. Bertram. 2001. “Contributions of Gait and Trunk Movements to Prehension: Perspectives from World- and Body-Centered Coordinates.” *Motor Control* 5 (2): 151–165.
Maynard, H. B., G. J. Stegemerten, and J. L. Schwab. 1948. *Methods-Time Measurement*. New York, USA: McGraw-Hill.
Meinhart-Shibata, P., M. Kramer, J. A. Ashton-Miller, and C. Persad. 2005. “Kinematic Analyses of the 180 Degrees Standing Turn: Effects of Age on Strategies Adopted by Healthy Young and Older Women.” *Gait Posture* 22 (2): 119–125.
Oberg, T., A. Karsznia, and K. Oberg. 1993. “Basic Gait Parameters: Reference Data for Normal Subjects, 10-79 Years of Age.” *Journal of Rehabilitation Research and Development* 30 (2): 210–223.
Orendurff, M. S., A. D. Segal, J. S. Berge, K. C. Flick, D. Spanier, and G. K. Klute. 2006. “The Kinematics and Kinetics of Turning: Limb Asymmetries Associated with Walking a Circular Path.” *Gait Posture* 23 (1): 106–111.
Patla, A. E., S. D. Prentice, C. Robinson, and J. Neufeld. 1991. “Visual Control of Locomotion: Strategies for Changing Direction and for Going over Obstacles.” *Journal of Experimental Psychology: Human Perception and Performance* 17 (3): 603–634.
Patla, A. E., A. Adkin, and T. Ballard. 1999. “Online Steering: Coordination and Control of Body Center of Mass, Head and Body Reorientation.” *Experimental Brain Research* 129 (4): 629–634.
Plamondon, A., A. Delisle, K. Trimble, P. Desjardins, and T. Rickwood. 2006. “Manual Materials Handling in Mining: The Effect of Rod Heights and Foot Positions When Lifting ‘In-the-Hole’ Drill Rods.” *Applied Ergonomics* 37 (6): 709–718.
Plamondon, A., D. Denis, A. Delisle, C. Lariviere, E. Salazar, and IRSST MMH research group. 2010. “Biomechanical Differences between Expert and Novice Workers in a Manual Material Handling Task.” *Ergonomics* 53 (10): 1239–1253.
Plamondon, A., C. Lariviere, A. Delisle, D. Denis, and D. Gagnon. 2012. “Relative Importance of Expertise, Lifting Height and Weight Lifted on Posture and Lumbar External Loading During a Transfer Task in Manual Material Handling.” *Ergonomics* 55 (1): 87–102.
Raschke, U., H. Kuhlmann, and M. Hollick. 2005. *On the Design of a Task-Based Human Simulation System*, Technical Paper 2005-01-2702, Warrendale, PA: SAE International.
Reed, M. P., and D. W. Wagner. 2007. *An Integrated Model of Gait and Transition Stepping for Simulation of Industrial Workcell Tasks*, Technical Paper 2007-01-2478, Warrendale, PA: SAE International.
Reed, M., J. Faraway, D. Chaffin, and B. Martin. 2006. *The HUMOSIM Framework: A New Approach to Human Motion Simulation for Ergonomic Analysis*, Technical Paper 2006-01-2365, Warrendale, PA: SAE International.
Samson, M. M., A. Crowe, A., P. L. de Vreede, J. A. G. Dessens, S. A. Duursma, and H. J. J. Verhaar. 2001. “Differences in Gait Parameters at a Preferred Walking Speed in Healthy Subjects Due to Age, Height and Body Weight.” *Aging Clinical and Experimental Research* 13 (1): 16–21.
Sparrow, W. A., and O. Tirosh. 2005. “Gait Termination: A Review of Experimental Methods and the Effects of Ageing and Gait Pathologies.” *Gait Posture* 22 (4): 362–371.
Sparrow, W. A., J. van der Kamp, G. J. P. Savelsbergh, and O. Tirosh. 2003. “Foot-Targeting in Reaching and Grasping.” *Gait Posture* 18 (1): 60–68.
Stolze, H., H. J. Friedrich, K. Steinauer, and P. Vieregge. 2000. “Stride Parameters in Healthy Young and Old Women–measurement Variability on a Simple Walkway.” *Experimental Aging Research* 26 (2): 159–168.
Taylor, F. W. 1911. *The Principles of Scientific Management*. New York: Harper & Brothers.
Taylor, M. J. D., P. Dabnichki, and S. C. Strike. 2005. “A Three-Dimensional Biomechanical Comparison between Turning Strategies during the Stance Phase of Walking.” *Human Movement Science* 24 (4): 558–573.
Taylor, M. J. D., S. C. Strike, and P. Dabnichki. 2006. “Strategies Used for Unconstrained Direction Change during Walking.” *Perceptual and Motor Skills* 102 (2): 576–588.
Terrier, P., and Y. Schutz. 2003. “Variability of Gait Patterns during Unconstrained Walking Assessed by Satellite Positioning (GPS).” *European Journal of Applied Physiology* 90 (5/6): 554–561.
Wagner, D. W., R. L. Kirschweng, and M. P. Reed. 2009. “Foot Motions in Manual Material Handling Transfer Tasks: A Taxonomy and Data from an Automotive Assembly Plant.” *Ergonomics* 52 (3): 362–383.
Wagner, D. W., M. P. Reed, and D. B. Chaffin. 2010. “The Development of a Model to Predict the Effects of Worker and Task Factors on Foot Placements in Manual Material Handling Tasks.” *Ergonomics* 53 (11): 1368–1384.
Wickel, E. E., and R. F. Reiser 2nd. 2008. “The Effect of Floor Slope on Sub-maximal Lifting Capacity and Technique.” *Applied Ergonomics* 39 (3): 296–304.
Winter, D. A. 1995. “Human Balance and Posture Control during Standing and Walking.” *Gait Posture* 3 (4): 193–214.
Xu, D., L. G. Carlton, and K. S. Rosengren. 2004. “Anticipatory Postural Adjustments for Altering Direction during Walking.” *Journal of Motor Behavior* 36 (3): 316–326.
van der Wel, R. P. R. D., and D. A. Rosenbaum. 2007. “Coordination of Locomotion and Prehension.” *Experimental Brain Research* 176 (2): 281–287.