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The development of a model to predict the effects of worker and task factors on foot placements in manual material handling tasks

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Accurate prediction of foot placements in relation to hand locations during manual materials handling tasks is critical for prospective biomechanical analysis. To address this need, the effects of lifting task conditions and anthropometric variables on foot placements were studied in a laboratory experiment. In total, 20 men and women performed two-handed object transfers that required them to walk to a shelf, lift an object from the shelf at waist height and carry the object to a variety of locations. Five different changes in the direction of progression following the object pickup were used, ranging from 45° to 180° relative to the approach direction. Object weights of 1.0 kg, 4.5 kg, 13.6 kg were used. Whole-body motions were recorded using a 3-D optical retro-reflective marker-based camera system. A new parametric system for describing foot placements, the Quantitative Transition Classification System, was developed to facilitate the parameterisation of foot placement data. Foot placements chosen by the subjects during the transfer tasks appeared to facilitate a change in the whole-body direction of progression, in addition to aiding in performing the lift. Further analysis revealed that five different stepping behaviours accounted for 71% of the stepping patterns observed. More specifically, the most frequently observed behaviour revealed that the orientation of the lead foot during the actual lifting task was primarily affected by the amount of turn angle required after the lift ($R^2 = 0.53$). One surprising result was that the object mass (scaled by participant body mass) was not found to significantly affect any of the individual step placement parameters. Regression models were developed to predict the most prevalent step placements and are included in this paper to facilitate more accurate human motion simulations and ergonomics analyses of manual material lifting tasks.

Statement of Relevance: This study proposes a method for parameterising the steps (foot placements) associated with manual material handling tasks. The influence of task conditions and subject anthropometry on the foot placements of the most frequently observed stepping pattern during a laboratory study is discussed. For prospective postural analyses conducted using digital human models, accurate prediction of the foot placements is critical to realistic postural analyses and improved biomechanical job evaluations.

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

1. Introduction

The results obtained from biomechanical analyses of manual material handling transfer tasks have shown the importance of knowing both body postures and foot placements (Bendix and Eid 1983, Authier *et al*. 1996, Delisle *et al*. 1996, 1998, Burgess-Limerick and Abernethy 1998, Kollmitzer *et al*. 2002, Plamondon *et al*. 2006, Wickel and Reiser 2008). For the analysis of existing jobs, posture data can be obtained from video or motion-capture data. But for proactive design of industrial tasks, the ability to predict whole-body posture and motion is needed (Chaffin *et al*. 2006) and such postural predictions are highly dependent on the location of the feet relative to the location of an object that is to be lifted. Although the development of frameworks for task-based human motion simulation has provided the opportunity for improved job design (see Badler *et al*. 2005, Raschke *et al*. 2005, Reed *et al*. 2006), these human motion algorithms all require the users to specify foot locations or stance with regard to the load. Unfortunately, guidelines for predicting appropriate foot positions are not well defined (Delisle *et al*. 1999, Kollmitzer *et al*. 2002).

Much of the research involving foot placements related to dynamic postural lifting analysis has focused on lifting capability and not lifting behaviours. Similarly, the capacity to maintain balance while statically holding different weights in varied locations has also been studied (Holbein and Chaffin 1997, Holbein and Redfern 1997, Lee and Lee 2003). These latter studies highlight the importance of balance in dictating the stance postures selected by subjects. Wu and MacLeod (2001) reported the effects on the position of the whole-body centre of mass when a weight was asymmetrically loaded on the right side of the body while foot stance width was varied. Gillette

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and Abbas (2003) demonstrated centre of pressure excursions across different reach directions for split stance postures as compared with parallel stance postures. The individual effects pertaining to lifting height, object weight, intended object trajectory and lifting speed on peak dynamic L5/S1 moments have been investigated for sagittal plane lifts, but all utilised pre-specified foot parallel stances (Buseck *et al.* 1988, Tsuang *et al.* 1992, Lavender *et al.* 2003). Asymmetric lifts utilising parallel foot stances have also been reported (Plamondon *et al.* 1995, Hooper *et al.* 1998), as well as asymmetric lifts over varied stance widths (Authier *et al.* 1995, Delisle *et al.* 1998). Although these studies provide useful insight on the biomechanics of the defined tasks, they are not useful for predicting how people will normally perform typical industrial tasks that include minimal constraints on foot placements during the act of lifting while approaching and progressing away from a shelf in different directions with the object being lifted.

In essence, the posture and motion prediction models currently available for predicting the biomechanical requirements of lifting tasks tend to apply to only a narrow range of lifting behaviours and most often require as input an initial posture or relative foot-to-object location (Ayoub and Lin 1995, Dysart and Woldstad1996, Hsiang and McGorry 1997, Ayoub 1998, Chang *et al.* 2001, Gundogdu *et al.* 2005). Interestingly, none of the posture prediction models reviewed includes the prediction of foot stance or relative foot placements. One potential reason for this limitation may be attributed to the methods used for predicting the remaining body posture once the foot-to-object location is specified. For example, models in which whole-body balance is optimised (Dysart and Woldstad 1996, Hsiang and McGorry 1997) may not be able to adequately reflect the observation that experienced handlers often support their body weight on a single foot throughout the lift, rather than using two feet (Ljungberg *et al.* 1989, Authier *et al.* 1996, Wagner *et al.* 2009).

Another important limitation of most lifting studies is the relatively small horizontal distance between the operator's starting location, object pickup location and the delivery location. In a review of 944 handling transfers in a distribution centre for a large transport company, Baril-Gingras and Lortie (1995) reported that workers took two or more steps in over half of the transfers (57%). Unfortunately, few of the previous studies cited have included pickup or delivery tasks separated by more than two steps. Two notable exceptions should be mentioned. In a study by Delisle *et al.* (1999), four stepping strategies involving multiple steps were used, but the study participants were instructed on the specific stepping strategy to use. On the other hand, Authier *et al.* (1996) analysed operator-selected transfer techniques with expert material handlers and allowed the participants to take as many steps as desired. Their interpretation of the results suggested that positioning of the feet could be a significant determinant in how the lift was executed. Additionally, their results suggest that movement prior to the actual lift (i.e. walking up to the object being lifted) may significantly affect the foot placements (and potentially the subsequent posture and/or movement during the lift). However, the experimental design did not explicitly define an approach or departure direction from the lifting or delivery locations, limiting the ability to draw quantitative conclusions relating stepping strategy to those task conditions. Although metrics related to foot support and positions were presented (i.e. number of foot supports during transfer and distance of heel to platform at beginning and deposit transfer times), the parameterisation used is insufficient to develop algorithms suitable for motion simulation.

Clearly, a large variety of stepping patterns (defined by the number of steps and their placement) are theoretically possible for people performing an object pickup or delivery task. However, from an in-plant observational study, only a small number of stepping behaviours appeared to be used by experienced operators to accomplish the majority of manual material handling transfer tasks encountered in a work-cell environment (Wagner *et al.* 2009). It should be noted that this latter study described foot placements using the Lexical Transition Classification System (L-TRACS), introduced by Wagner *et al.* (2009). This system provides a concise notation for describing the sequence of steps relative to an object pickup or placement and the critical type of foot support used at the time of load transition (e.g. left foot support, right foot support or support from both feet). Using this method, Wagner *et al.* (2009) found that the majority of object transfers studied in the automotive assembly plant involved picking up or placing an object with only one of the operator's feet in contact with the ground. This further underscores the importance of understanding freely chosen lifting behaviours when attempting to use biomechanical guidelines and models to predict the risk of injury in manual material handling jobs.

The current paper begins by presenting a general methodology for quantitatively describing foot positions and orientations used during manual material handling transfer tasks. This methodology is applied to a laboratory study, wherein the object weight and directions of the subject approach and progression are varied. The results from the laboratory study are used to investigate and quantify individual and interactive effects of the task and operator characteristics on foot placements for two-handed object pickups.

2. Method

Participants moved boxes with a range of weights between pickup and delivery locations while their whole-body motions were recorded. The participants lifted the boxes from a shelf set to 53% of stature above the ground (approximately waist height). By varying the pickup, delivery and participant start locations, the approach and delivery azimuths were varied. Delivery and start location distance to the pickup location were scaled to a nominal step distance measured during preliminary trials. Only results pertaining to the pickup conditions are presented here. Figure 1 shows a participant demonstrating a typical stance at the moment of load pick-up.

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. They had no special experience working in a manual materials handling capacity. The study protocol was approved by an institutional review board and all participants provided written and informed consent.

The resulting subject pool consisted of 10 male and 10 female participants with mean (SD) age of 20.7 (1.3) years and 23.9 (5.3) years, respectively. Their statures were 181.1 (9.3) cm and 167.5 (6.8) cm and they had a BMI of 25.4 (4.1) kg/m^2 and 21.6 (2.6) kg/m^2, respectively. The participants ranged from 17 percentile to 99 percentile by stature for the male subjects and 31 percentile to 99 percentile by stature for the female subjects (Roebuck 1995).

2.2. Experimental facilities

A six-camera Qualisys Proreflex 240-MCU passive optical motion tracking system (Qualisys, Gothenburg, Sweden) was used to capture kinematics 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 shoes of the participants 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.

A total of 29, 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 (Figure 2). Markers placed on the lateral

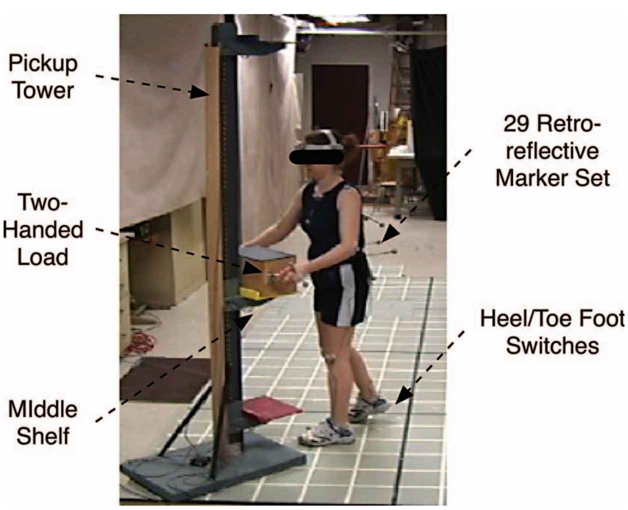

Figure 1. Participant in the test facility, showing pickup tower, two-handed load and motion capture markers and timing sensors.

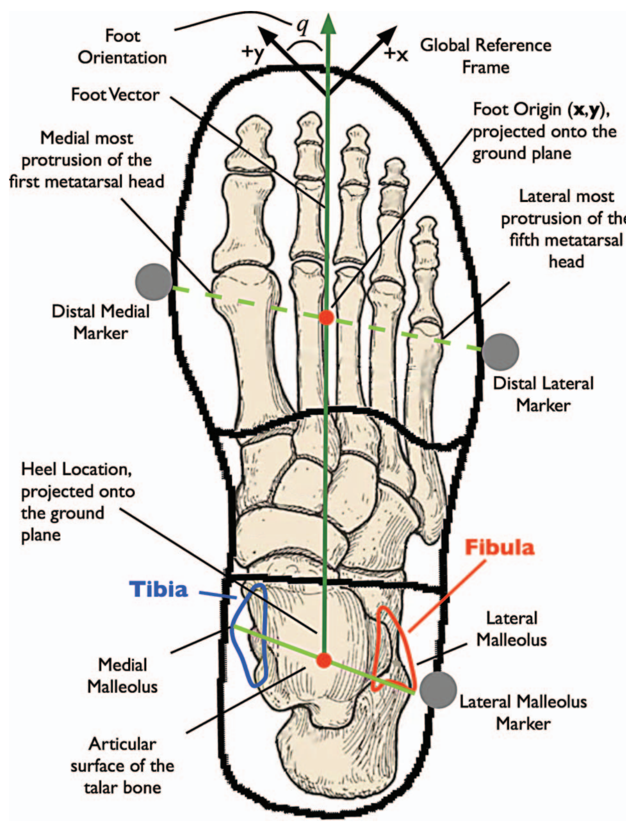

Figure 2. Marker placements on feet with regard to foot landmarks used to calculate global foot position and orientation.

and medial distal end and the lateral malleolus were used to create a local coordinate reference frame for each foot. The distance between the lateral and medial malleoli was measured and used as the offset for the distance from the lateral malleolus marker to estimate the heel joint centre. The foot position (x,y), projected to the ground plane, was calculated as the midpoint between the lateral and medial distal foot markers. The foot orientation (q) in the ground plane was calculated as the angle between the global + y coordinate vector defined by the shelf/object orientation and the vector defined by the foot position and heel joint centre (projected to the ground plane).

2.3. *Test conditions*

For each trial, the subjects picked up a box from one shelf and moved it to another with two hands. Each trial was defined by approach angle, departure angle and object weight. A representative trial is shown in Figure 3. Subjects approached the box located on the shelf from three to four steps away, picked up the box, transferred it to another shelf located at least three nominal steps away and returned to the initial start position.

The start and shelf tower locations for each test configuration are graphically depicted in Figure 4. The

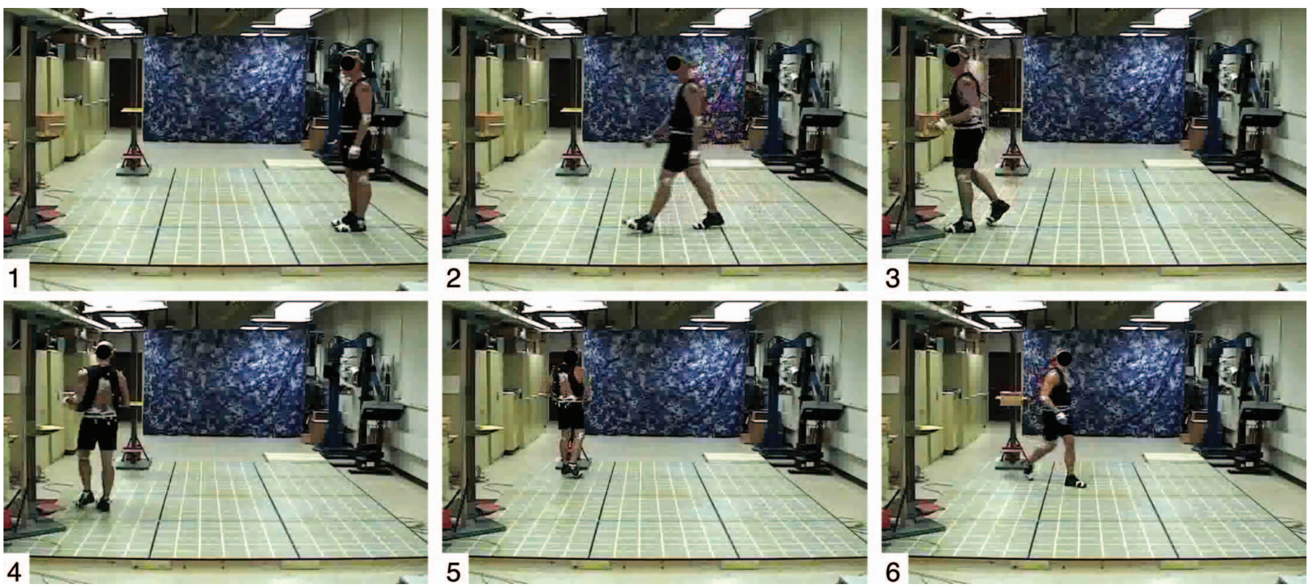

Figure 3. Participant performing a typical pickup and delivery transfer trial (1–6). Participant is: 1) at the start location waiting to begin; 2) approaching pickup tower; 3) picking up the load; 4) carrying load to delivery tower; 5) delivering the load; 6) returning to the start location.

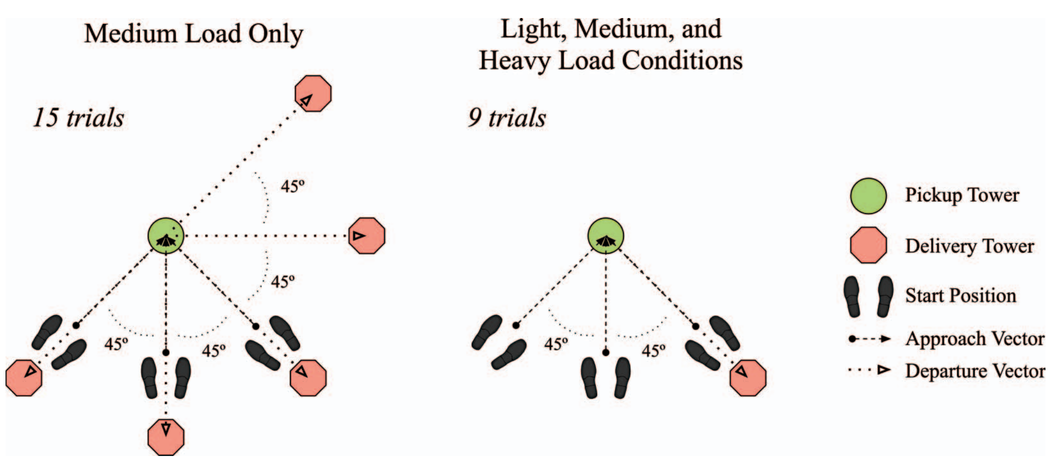

Figure 4. Experiment start and delivery conditions. Distances are not drawn to scale. Duplicate test conditions between the two trial blocks were collected only once in the 9-trial block.

two-hand load had horizontal cylindrical handles with diameters of 3.8 cm located 29.5 cm apart. The object weights were 1.0, 4.54 and 13.61 kg. The 4.5 kg (10 lbs) and the 13.6 kg (30 lbs) loads were selected to span the range of objects manipulated in many industrial work cells. The light load conditions were constructed to provide a 'no-weight' condition, similar to those objects defined as negligible weight in previous studies (Wagner *et al*. 2009). The colour of each two-handed load was uniquely associated with the weight so participants could visually identify which load weight was being used prior to the start of each trial (Figure 5). The approach and depature angles for each trial were defined based on the two-handed box orientation as depicted in Figure 6. The order of presentation of trials was randomised within each turn-angle block and the order of blocks was randomised. Two sets of full factorial trial conditions were collected

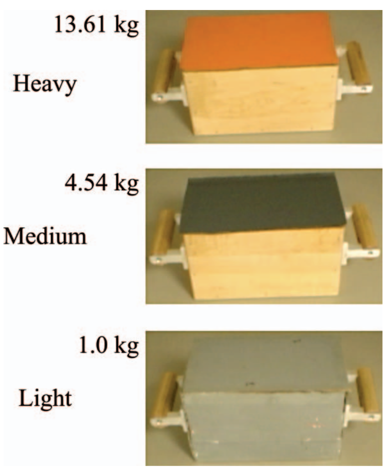

Figure 5. Light, medium and heavy objects used during the laboratory experiment. All two-handed boxes were the same size, with colour coding to denote object weights.

Table 1. Trial conditions for the experiment.

Number of trials	Approach angle*	Departure angle*	Delivery distance†	Object weight
9	+135 180 −135	+135	*Constant*	Light Medium Heavy
15	+135 180 −135	+45 +90 +135‡ 180 −135	*Constant*	Medium

*Angles are defined by shelf orientation; see Figure 6 for a definition of the angle system used here.
†Location defined by the midpoint between the shelf locations for which the 3–4 step transition and 4–5 step transition occurs.
‡The +135° departure angle trials were collected only once in the 9-trial block and not repeated for the 15-trial block.

and are summarised in Figure 4 and Table 1. The first full factorial trial set (referred to herein as the '9 trial block') consisted of all three load conditions and three approach/departure angle conditions. The second full factorial trial set (referred to herein as the '15 trial block') consisted of the medium load condition and all 15 approach/departure angle conditions.

2.4. Procedures

Participants attended two data collection sessions held 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 load/angle combination 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 practice load transfer session with the following experiment configuration, approach angle of 180°, departure angle of +135°, medium weight object, the delivery distance was varied by the experimenter to find the shelf locations that corresponded to the participant transitioning from 0–1, 1–2, 2–3, 3–4 and 4–5 steps to complete the transfer. Those step transitions were recorded and used to scale the approach and delivery distances for the second session to normalise the transfer distances across subjects to self-selected values defined by the number of steps. Specifically, the midpoint between the shelf locations for the 3–4 and 4–5 step transitions were used to scale subject start, subject end and shelf locations. In addition to recording the step transitions for the

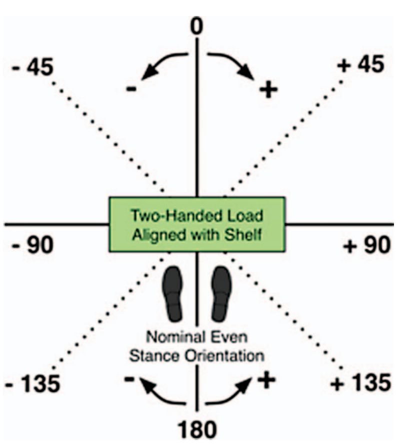

Figure 6. Definition of angle system used for defining the approach and departure angles.

two-handed medium load along a departure angle of $+135°$, the participants also practised transfers with all the weight combinations. The first session lasted approximately 2 h for each participant.

The second session consisted primarily of object transfers in which the participant's whole-body motion was recorded. The subjects were instructed to not perform any potentially fatiguing activity the day before participating in the second session (example activities of rock climbing and long distance running were given). At the beginning of the session, 29 retro-reflective markers were affixed to the participant and the subject was asked to perform three range-of-motion trials lasting 20 s each to aid in the subsequent automatic identification of the optical markers following the data collection period.

The second session lasted approximately 5 h. Each manual material handling transfer trial lasted 12 s. Prior to each trial, the participant was instructed to stand at a prescribed start location. The subjects were then reminded of the object weight (light, medium or heavy). 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 as a signal for the subject to begin the transfer trial. Following the pickup and delivery, the participant was instructed to return to the start location facing the same direction as at the beginning of the trial until the LED light signalled the trial was completed. The pace of each transfer trial was not explicitly controlled and was self-selected by each participant. Each participant was instructed to perform the transfer task at a pace that was comfortable and could be maintained over an 8-h workday.

2.5. *Quantitative Transition Classification System*

The pattern of foot motions (stepping behaviour) used in each trial was classified using the L-TRACS method as defined in Wagner *et al.* (2009). L-TRACS defines a descriptive representation of the transition stepping behaviour, which provides a consistent vocabulary for manual material handling stepping patterns. Similar accepted terms and vocabularies currently exist for grip posture (Schlesinger 1919, Cutkosky and Wright 1986), cyclic walking (Whittle 2002) and, to a lesser extent, turning during gait (Huxham *et al.* 2006). Unlike previous descriptions, L-TRACS describes many of the observed, non-cyclical stepping behaviours for manual material handling tasks. A summary of the L-TRACS nomenclature and elements relevant to this study are presented here. A complete description of the L-TRACS is presented in Wagner *et al.* (2009).

An L-TRACS description describes the steps that define the terminal stance at the manual material handling 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 weight of the object is initially borne by the lifter at pickup or by the shelf at delivery). Ipsilateral and contralateral limbs are defined with regard to the turn direction. The L-TRACS uses a qualitative code to succinctly describe each step and the terminal stance.

L-TRACS documents the pattern of steps during a materials handling task and is useful for when comparing and grouping behaviours with similar step progressions, but more quantitative specificity is needed for modelling. For example, L-TRACS describes the number of steps and their sequence, but does not specify the locations of the steps. A Quantitative Transition Classification System (Q-TRACS) methodology was developed to compliment L-TRACS to accommodate this need. Q-TRACS defines a unique set of relative foot positions and timed foot events (heel contact, toe contact, heel lift and toe lift) for each footstep. A footstep in Q-TRACS describes the contact of a foot with the floor, the stance interval and the departure of the foot from the floor. Eight parameters, defined below in the vector $\boldsymbol{F}$, are used to represent each step. Vector $\boldsymbol{F}$ is given by:

$$\mathbf{F} = \left[\mathrm{f},\ \mathrm{T_x},\ \mathrm{T_y},\ \mathrm{q},\ \mathrm{t_{hc}},\ \mathrm{t_{tc}},\ \mathrm{t_{hl}}, \mathrm{t_{tl}}\right]$$

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

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

$$\boldsymbol{S} = [\boldsymbol{F}_1, \boldsymbol{F}_2, \ldots, \boldsymbol{F}_n]^T$$

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

$$\mathbf{S} = [\mathbf{S}_R, \mathbf{S}_L]$$

The sequence of $\boldsymbol{F}$ in $\boldsymbol{S}_n$ is temporal, such that all t_i in $\boldsymbol{F}_j$ are strictly less than any t_i in $\boldsymbol{F}_{j+1}$.

The definition of $\boldsymbol{F}$ also is facilitated by a parameterisation that defines the positions and orientations of each foot with regard to a direction of the progression vector. Different steps in the step matrix $\boldsymbol{S}$ (sequence of steps) can be defined relative to a different direction of progression (or orientation frame). Huxham *et al.* (2006) proposed a similar method for defining selected spatial parameters for non-linear walking (i.e. cyclic walking with a defined change of direction).

An example in which the Q-TRACS parameterisation is applied to a manual material handling transfer task is graphically depicted in Figure 7. The direction of turn following the manipulation for the stepping pattern illustrated in Figure 7 is a turn toward the right. The rightward turn direction defines the contralateral limb as the left leg and the ipsilateral limb as the right leg. The first two steps in Figure 7 are referenced with regard to the approach vector (direction of progression prior to transfer) and the final step is referenced with regard to the departure vector (direction of progression after the transfer is completed). The example parameterisation uses the manipulation location and approach orientation frame (i.e. approach vector) to define the position of step 2 (i.e. lead foot during terminal stance), the approach orientation frame and the position of step 2 to define the position of step 1 and the departure orientation frame and the position of step 2 to define the position of step 3. Step orientation angles are defined as the angle (in the ground plane) between the step orientation vector (see Figure 2 for definition) and the orientation frame in which the spatial foot parameters are defined. An increase in the step orientation angle for the right foot corresponds to a clockwise rotation of the foot in the ground plane. An increase in the step orientation angle for the left foot corresponds to a counter-clockwise rotation. For symmetric straight line walking, a negative step orientation angle corresponds to inwardly rotated feet (i.e. toes pointing toward the direction of progression vector). Table 2 defines the corresponding step matrix S, the orientation frame(s) used to spatially define each foot and the origin location that each step position is referenced from for the stepping motion depicted in Figure 7.

2.6. *Data analysis*

Transition behaviours (defined in L-TRACS) were automatically identified using a computer algorithm implementing the step criteria described in Wagner *et al.* (2009). The state of each foot (i.e. both heel and toe in contact with the ground, only heel in contact with the ground, only toe in contact with the ground and neither heel nor toe in contact with the ground) at

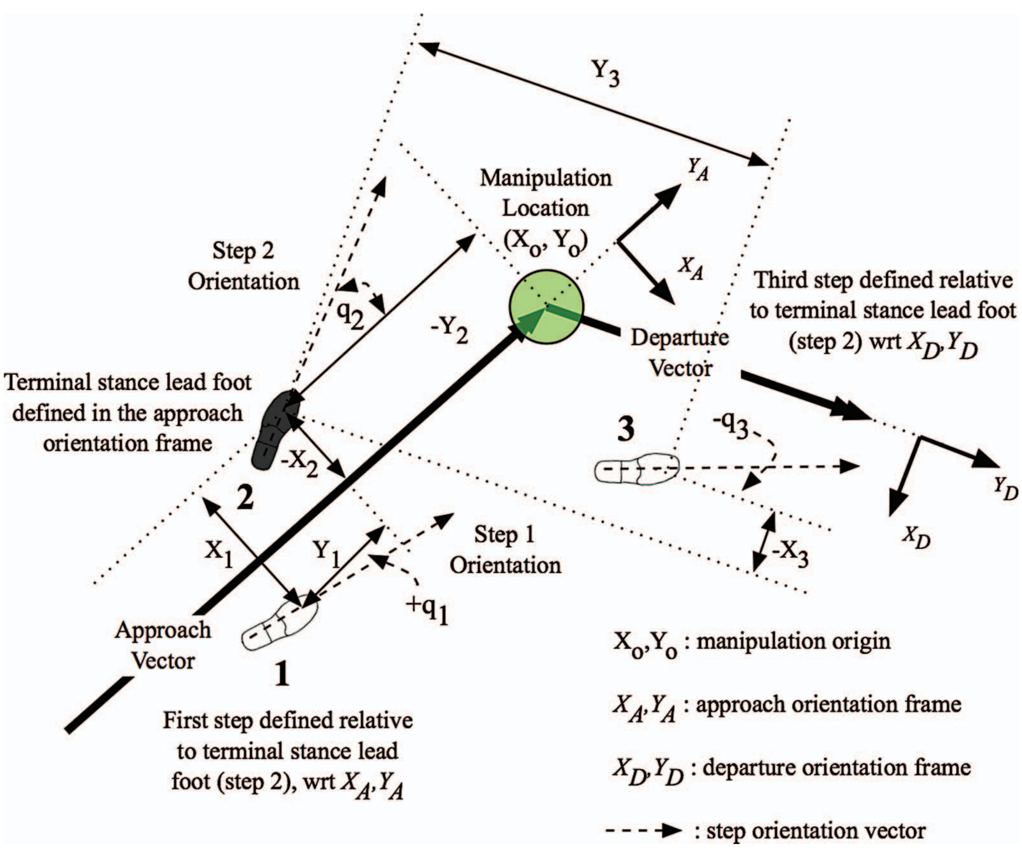

Figure 7. Parameterisation of a representative split stance transition behaviour. Approach and departure orientation frames have origins at the manipulation location but are drawn offset for clarity.

Table 2. Step matrix S for the stepping motion depicted in Figure 7.

Step Number	Orientation frame used to define step position orientation	Origin location step position is referenced from	Foot	X-Position	Y-Position	Step Orientation	Heel Contact	Toe Contact	Heel Lift	Toe Lift
1	Approach (X_A,Y_A)	Step 2	Right	X_1	Y_1	$+q_1$	t_{hc1}	t_{tc1}	t_{hl1}	t_{tl1}
2	Approach (X_A,Y_A)	Manip. Location (X_0,Y_0)	Left	$-X_2$	$-Y_2$	$+q_2$	t_{hc2}	t_{tc2}	t_{hl2}	t_{tl2}
3	Departure (X_D,Y_D)	Step 2	Right	$-X_3$	Y_3	$-q_3$	t_{hc3}	t_{tc3}	t_{hl3}	t_{tl3}

every time step was identified using the footswitch data, which then allowed a precisely defined terminal stance period at each object pickup. Foot placement and orientation (defined by the projection of the ball of foot and ankle joint on to the ground plane, Figure 2) for the most frequently observed transition behaviours are described to illustrate the application of Q-TRACS (Figure 7). Each foot position is parameterised by three variables: lateral position (X_i); fore–aft position (Y_i); orientation (q). Foot positions before and after load pickup are defined in the approach and departure orientation frames, respectively. The approach direction of progression (used to calculate the approach orientation frame) is calculated as the vector in the ground plane defined by the pelvis location at the beginning of the trial and the object pickup location. The departure direction of progression is calculated as the vector in the ground plane defined by the pelvis location at the time of object pickup and the location of the subsequent delivery target. The approach and departure vectors are used to calculate approach and departure orientation frames (see Figure 7 for example), respectively, with the reference frame origins collocated at the pickup location (manipulation location in Figure 7). Each pickup or delivery location was calculated as the location of the average of the grip centres at the instant the load was transferred (measured by the change in state of the pressure switch located on the pickup shelf). Manipulation location, instead of pelvis location at the time of object pickup, is used to define the approach vector because one goal of this parameterisation is that it can be readily utilised with predictive motion models that often use the pelvis as the root for defining the location of a person in space. Unfortunately, pelvis location may not be known a *priori*. Reed *et al*. (2006) has suggested that end-effector constraints, such as those defined by Q-TRACS, may be used to calculate pelvis location for the terminal posture. Such a modelling framework is assumed here for future predictive models and is the reason the pelvis location (and not the pickup location) is used to define the departure vector.

Lead foot placement and orientation (for split-stance behaviours), the midpoint position between the feet (for parallel-stance behaviours) and the relative step length, step width and step orientation measured with regard to the direction of progression for all the steps included in similar behaviours were investigated. Figure 7 shows an example Q-TRACS parameterisation for a representative split-stance behaviour. The reference frames (approach and departure) are offset along the respective direction of progressions for clarity in the figure. However, both frames are collocated and share an origin at the manipulation location.

The effects of turn angle and object weight on the foot positions are presented for the most commonly observed stepping behaviour for clarity. Specifically, the effects of each of the task factors on each of the nine variables used to parameterise that behaviour are discussed.

3. Results

3.1. Distribution of transition behaviours

Wagner *et al*. (2009) demonstrated that a small number of stepping behaviours account for a large percentage of transition stepping patterns observed in work-cell tasks. The distribution of observed stepping behaviours (defined using L-TRACS) in the current laboratory study is presented in Figure 8. The most frequent stepping behaviour was observed in 42% of trials (shown separately as 0.37 and 0.45 cumulative density for the 9- and 15- trial blocks in Figure 8, respectively). The most frequent stepping behaviour consisted of a split stance (at load pickup) with the trailing leg corresponding to the same side of the body as the direction of turn. The second most frequent behaviour (second column from left in Figure 8) was observed to have a similar terminal split stance as the most frequently observed behaviour, but with an additional step (total of four steps in the behaviour) following the pickup to accomplish the change in direction. None of the remaining 25% of stepping behaviours was observed in more than 2% of the pickup transfers. The majority of those remaining

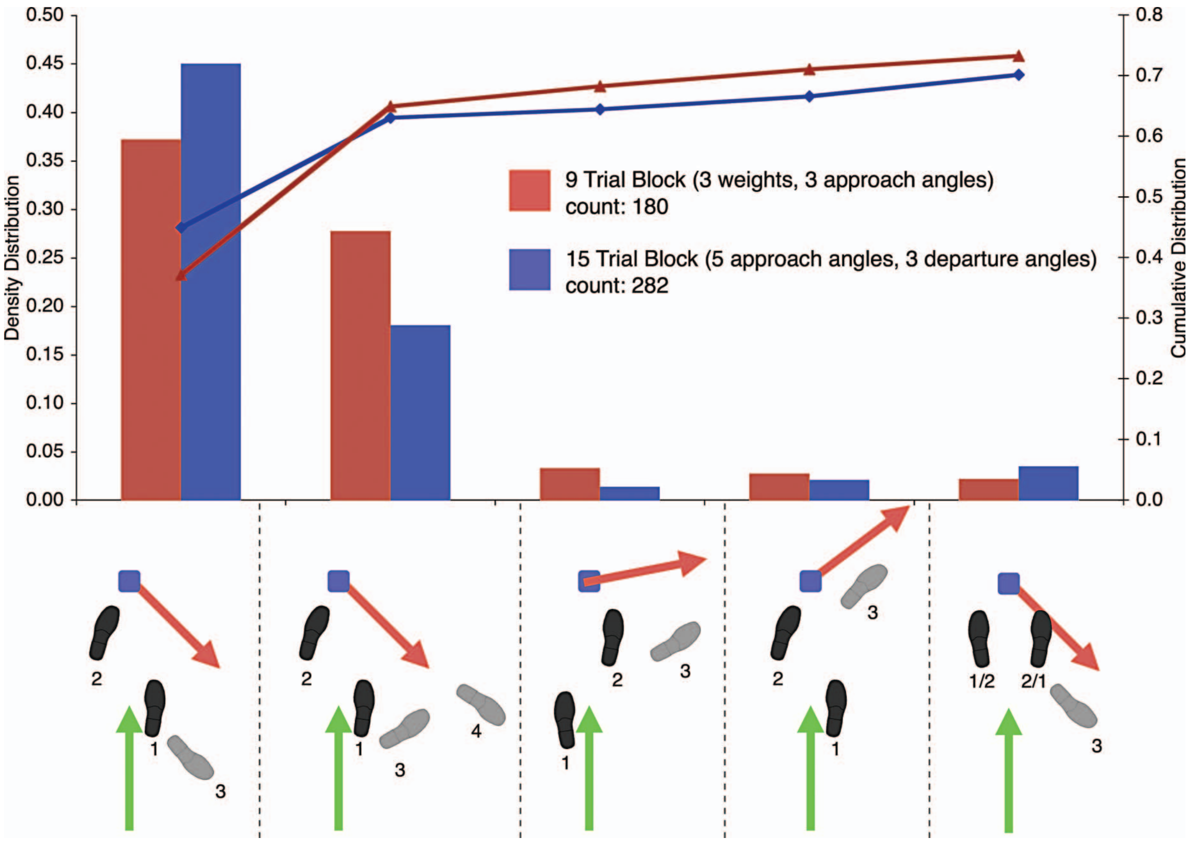

Figure 8. Absolute and cumulative distributions of the five most frequently used Lexical Transition Classification System behaviour groups for the 9- and 15-trial blocks. The first and second most frequently used behaviour groups (first and second columns from the left) were the same for both trial blocks.

stepping behaviours used four or more steps to accomplish the pickup transfer. Interpretations of the effects of task and anthropometric factors on foot placements are presented for the most frequently observed stepping behaviour.

3.2. *Effects of task and subject variables on foot placements for the most common stepping behaviour*

The most frequently observed stepping behaviour was used to investigate the effects of turn angle and object weight on the positions and orientations of the foot placements during the behaviour. The 'one-step' step behaviour group (left side of Figure 8) can be described as follows:

> The transition behaviour begins with a step by the ipsilateral foot, followed by a step with the contralateral foot (i.e. foot opposite the direction of turn), at which time the load is picked up while the lower extremities are in a split-stance posture with the contralateral foot as the lead foot, followed by a step with the ipsilateral foot along the new direction of progression.

Three variables for each step (X_i, Y_i, q_i), totalling nine variables, are analysed here. As previously described, the parameterisation of the third step of this behaviour is defined in the departure coordinate system and hence partially includes the effects of turn angle.

The results are presented in the following subsections:

(1) Independent effects of turn angle for each of the nine step variables.
(2) Independent effects of object weight for each of the nine step variables.
(3) Interaction effects and ANOVA between turn angle, object weight, stature and BMI for each of the nine step variables.

3.2.1. *Effects of turn angle*

A subset of the full 15 trial block set in which the one-step stepping behaviour was observed was used to investigate the effects of turn angle. Distributions of the transfer trials used in the analysis by subject

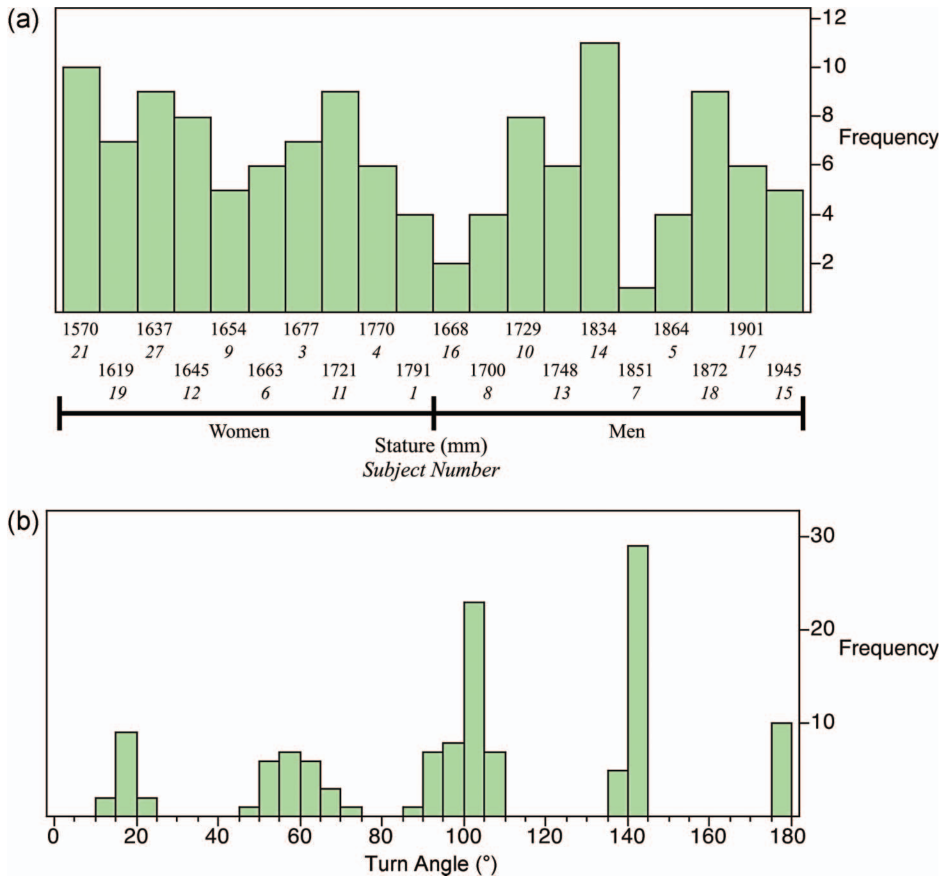

Figure 9. Distributions of transfer trials used to investigate the effects of turn angle on the foot positions and orientations for the one-step stepping behaviour. Transfer trials are grouped by (a) subject number and (b) observed turn angle.

number and observed turn angle are presented in Figure 9.

A linear regression between turn angle and each stepping parameter is presented in Figure 10. A linear fit of turn angle was observed to be a significant ($p < 0.01$) predictor with an R^2 adjusted value greater than 0.1 for the X_1, X_2, X_3, Y_3, q_1, q_2 and q_3 stepping behaviour parameters. Turn angle did not significantly affect the stance phase step parameters associated with the fore–aft distance (Y_1 and Y_2). However, turn angle significantly affected the lateral placement of all the steps, as well as the orientation of each foot. The linear fit predicts that increasing the turn angle from 20° to 180° after the pickup results in a 50° average decrease (e.g. increased inward rotation) in foot orientation for the lead foot (q_2) at load pickup. The plot in Figure 10c also suggests that for the defined 180° turn, the magnitude of the lead foot orientation (q_2) may be underestimated by the linear fit. The same trend observed between turn angle and q_2 is also observed for the orientation of the final step (q_3), although to a significantly smaller magnitude. This suggests that, for larger turns, participants primarily aggregate the necessary change in orientation between the q_2 orientation and the following two steps (i.e. q_3 and the following step). A significant trend was also observed between the orientation of the first step and turn angle, in which an increase in turn angle from 20° to 180° corresponded with an average increase in external rotation of the first step by 10°. The linear fits suggest that the majority of the orientation change is accomplished during the third step (i.e. when both hips are being externally rotated). However, the large range over which q_2 is observed also suggests that certain participants may favour a strategy in which larger internal hip rotation (by pre-orienting the lead foot) is the primary means for producing the change in heading.

The lateral foot placements of each step (X_1, X_2 and X_3) were also significantly affected by changes in turn angle. The X_1 and X_2 positions are further moved in the ipsilateral direction with regard to the load for small turn angles, in part because the pickup shelf obstructed the direct progression for small changes in direction. This same reasoning may also partly explain the larger step widths observed for the final step (X_3)

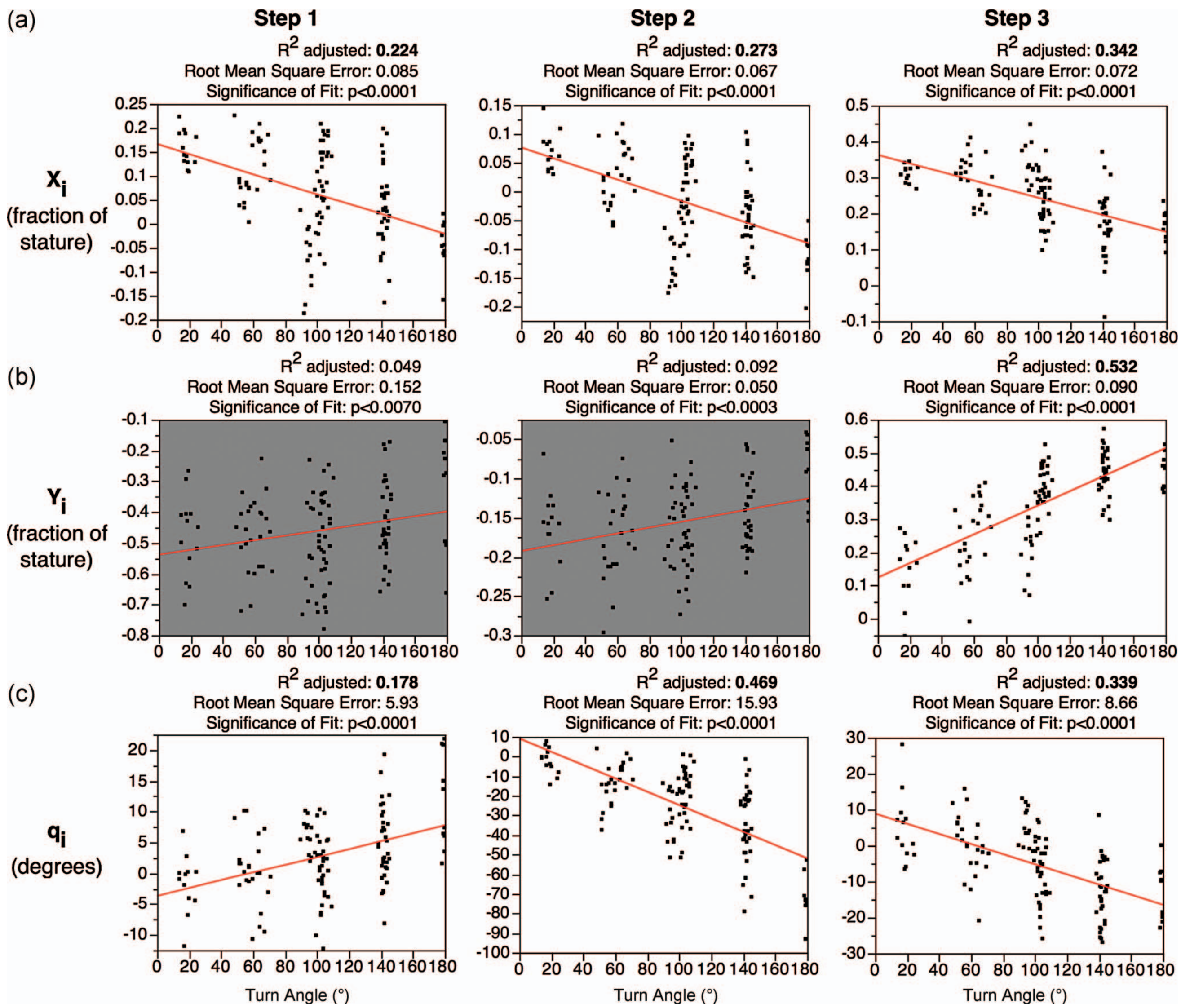

Figure 10. Bivariate plots of the nine stepping parameters of the one-step stepping behaviour (see Figure 7) by turn angle. Single factor regressions on turn angles and summary statistics are depicted for each stepping parameter. Greyed out plots indicate the linear fit was not significantly different ($p < 0.01$) from the mean parameter value and/or that the variance accounted for by the fit model (R^2 adjusted) was less than 0.1.

for small turn angles as compared with larger changes in orientation in which the pickup shelf did not act as an obstruction.

3.2.2. *Effects of object mass*

A subset of the full 9-trial block set in which the one-step stepping behaviour was observed was used to examine object mass effects. Distributions of the transfer trials used in the analysis by subject number, object mass (normalised by body mass) and observed turn angle are presented in Figure 11.

A linear regression analysis was carried out for the normalised object mass, predicting each stepping behaviour parameter. Using the same criteria of significance applied previously ($p < 0.01$ with an R^2 adjusted value greater than 0.1), no stepping behaviour parameters were found to be significantly predicted by changes in relative object mass. Slight trends were observed for Y_2 and X_3, corresponding to a decrease in step size and step width, respectively, with an increase in object mass.

3.3. *Effects of task and subject characteristics: ANOVA*

Multivariate regression models for each stepping parameter were generated to investigate potential

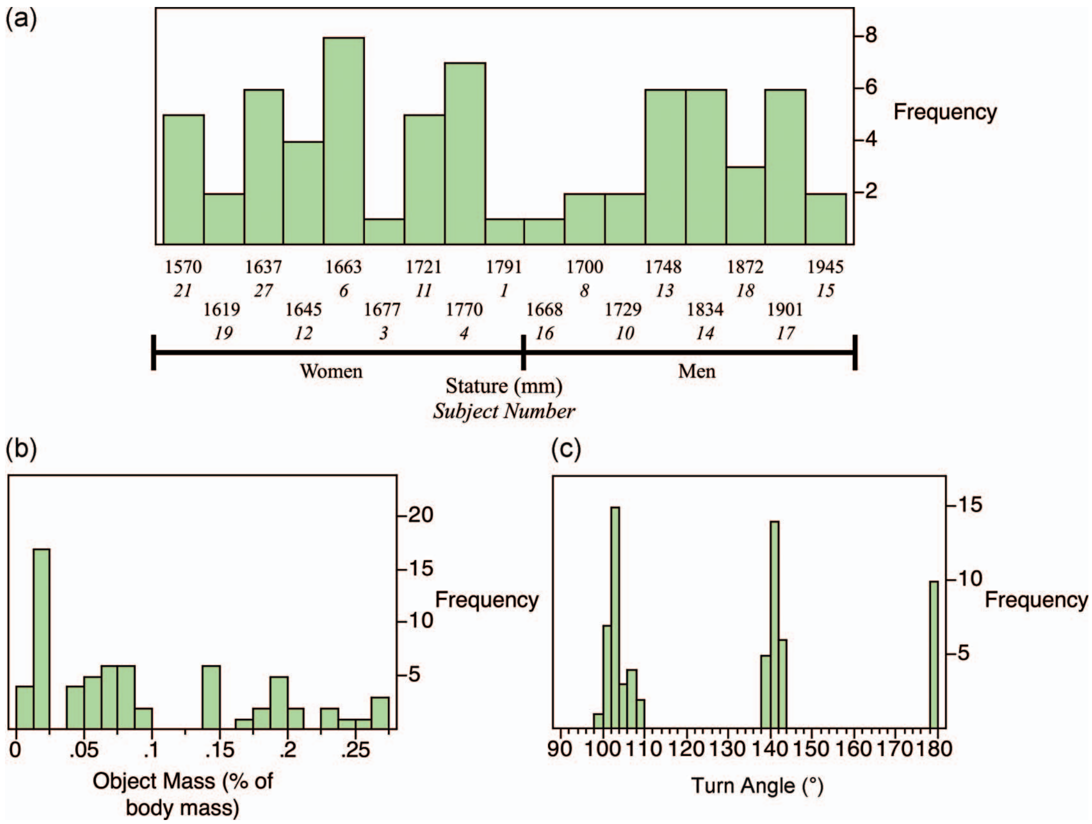

Figure 11. Distributions of transfer trials used to investigate the effects of object mass on the foot positions and orientations for the one-step stepping behaviour. Transfer trials are grouped by (a) subject number, (b) object mass and (c) observed turn angle. Note that subject numbers 5, 7 and 9 did not use the one-step behaviour for the transfer trials investigated here.

interactions between the subject and task characteristics. The same subset of data from the 15-trial block used to investigate the independent effects of turn angle on the one-step stepping behaviours was used. Two-way interactions were included for all tasks and anthropometric variables to examine the possibility that a particular step variable was scaled differently for different subjects and task conditions. A step-wise procedure for model creation was applied using, first, an automated procedure with $p < 0.01$ to enter and $p < 0.05$ to leave and, second, an interactive procedure, during which the contribution of included terms was evaluated in an effort to obtain a more parsimonious model. Terms were considered important and included in the final prediction model if they (or an associated higher order term) were statistically significant with $p < 0.01$ and contributed to an increase in adjusted R^2 value of at least 0.02 compared with the corresponding model with the term excluded.

Two tables are presented for each of the nine dependent measures evaluated. The resulting regression models are tabulated and the coefficients for the significant terms, regression function intercept, adjusted R^2 value and the root mean square error (RMSE), are presented in the first table (Table 3). The regression coefficients are multiplied by the range of the continuous independent measures present in the data and presented in the second table (Table 4) to provide a meaningful estimate of their relative importance. Regression coefficients that involve quadratic terms are presented for the combined effect of the linear and second order effects over the ranges observed in the data. The range table allows for the direct interpretation of the effects of varying the task variables over the observed range in the data on the dependent measures.

BMI, defined as the body mass of the subject divided by the square of the stature (kg/m^2), is used in place of body mass alone to include a representation of body mass that is less correlated with stature. The correlation between BMI and stature for the subjects included here is 0.26 (as compared with a correlation coefficient of 0.72 between stature and body mass). Distance measures are all normalised by subject stature. Object mass is normalised by subject body mass to facilitate direct comparisons across subjects, as suggested by Pierrynowski and Galea (2001).

Table 3. Regression equations predicting the step variables for the one-step stepping behaviour (original data from the 15 block trial)*.

Variable	X_1	Y_1	q_1	X_2	Y_2	q_2	X_3	Y_3	q_3
Intercept	0.167	−0.178	−14.96	0.077	−0.099	16.77	0.211	−0.328	−50.5
Turn angle (°)	−1.04e-3	1.03e-3	0.0578	−9.26e-4	4.66e-4	−0.363	−1.15e-3	2.28e-3	−0.145
Object mass (fraction of body mass)	–	–	–	–	–	–	–	–	324.6
Stature (mm)	–	−2.9e-5	–	–	–	–	–	2.56e-4	–
BMI (kg/m^2)	–	−0.0163	0.532	–	−5.29e-3	–	6.42e-3	–	1.65
Turn angle ∧2†	–	1.54e-5	–	–	6.2e-6	−2.48e-3	–	–	–
BMI ∧2†	–	–	–	–	7.28e-4	–	–	–	–
Stature × BMI†	–	1.49e-4	–	–	–	–	–	–	–
R^2 (adjusted)	0.22	0.27	0.19	0.27	0.21	0.53	0.40	0.57	0.44
root mean square error	0.09	0.12	6.2	0.07	0.05	14.9	0.07	0.09	7.98

–Indicates that the model coefficient was not significantly different from zero.

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

†Variable values included in the interaction terms were centred to their mean value observed in the data to ensure the mean value was not involved in the inclusion of the interaction to the fit model.

Table 4. Range estimates using regression equations for the one-step stepping behaviour (original data from the 15-block trial).

Variable	Range	X_1	Y_1	q_1	X_2	Y_2	q_2	X_3	Y_3	q_3
Turn angle (°)	166.2	−0.173	0.194‡	9.6	−0.154	0.083‡	−56.9‡	−0.191	0.379	−24.1
Object mass (fraction of body mass)	0.0501	–	–	–	–	–	–	–	–	16.3
Stature (mm)	375	–	†	–	–	–	–	–	0.096	–
BMI (kg/m^2)	14.6	–	†	7.77	–	−0.053‡	–	0.094	–	24
R^2 (adj.)*	–	0.22	0.27	0.19	0.27	0.21	0.53	0.40	0.57	0.44
RMSE*	–	0.09	0.12	6.2	0.07	0.05	14.9	0.07	0.09	7.98

RMSE = root mean square error.

–Indicates that the model coefficient was not significantly different from zero.

*Values repeated from Table 3.

†Variables involved in interaction effect.

‡Variables involved in second order effect. Range estimate is the combined effects for the linear and second order terms over the ranges observed in the data (i.e. minimum or maximum effect may not occur at range limits.

Turn angle was entered as a significant variable for each of the stepping variable models, including Y_1 and Y_2, which were identified to not have a significant relationship in the previously presented linear models (Figure 10). Anthropometric effects related to stature were observed for the normalised step-length parameters of Y_1 and Y_3, suggesting that length normalisation by stature may be insufficient to account for anthropometric effects. Non-linear effects that entered the final regression models were observed for BMI and turn angle and included in the Y_2 fit model and in the fit models for the Y_1, Y_2 and q_2 stepping parameters, respectively. One interaction involving stature and BMI was included for the Y_1 regression model.

The range estimates, R^2 values, and RMSE values in Table 4 indicate the relative importance of the anthropometric and task variables in determining foot placements and orientations for the one-step stepping behaviour. X_1, Y_1 and q_1 are predicted only moderately well (e.g. adjusted R^2 of 0.27 for step length). The most powerful predictor of X_1 is turn angle, with larger turn angles being associated with smaller step widths (approaching and including slightly negative 'cross-over' steps) between the first and second steps. The final q_1 prediction model includes turn angle and BMI. Individuals with a larger BMI tended to have a larger foot angle (outward rotation) with regard to the measured direction of progression. The fore–aft placement of the first step, Y_1, had the best overall model fit of the first step stepping variables. The most significant predictor of Y_1 was BMI, suggesting the step length directly preceding the act of lifting a load was subject dependent, potentially having a similar anthropometric relationship to observations for normal gait (Stolze *et al.* 2000, Zverev 2006). However, the relatively large RMSE value (largest for all observed step length-based variables) of

0.12 suggests that the variation observed in the data is large for the step length prior to when the load is lifted.

The q_2 step variable is better predicted (adjusted R^2 of 0.53) than X_1, Y_1 and q_1 by the test variables, with turn angle being the most powerful predictor. Larger magnitudes of turn angle following load pickup tended to result in larger internal rotation of the lead foot prior to the lift. However, the relatively large RMSE of 14.9 in addition to the high adjusted R^2 value associated with the q_2 fit model suggests that q_2 varies over a large range of angles and that the remaining variation after the fit is applied is still quite substantial. Normalisation to subject-specific foot orientation angles during straight line walking may help lower the RMSE associated with the global deviation (with regard to direction of progression).

The fore–aft distance between the lead foot and load is not well predicted by the test and anthropometric variables. However, the relatively low RMSE (0.05) suggests the variance in the observed data is also small, potentially attributed to the null model parameterisation (i.e. normalisation by stature and distance measures defined along direction of progressions), which is not reflected in the adjusted R^2 values. Turn angle (combined linear and higher order effect) affected Y_2 approximately 1.5 times the amount caused by the BMI regressor (Table 4). For example, multiplying the Y_2 entries in Table 4 by an average stature of 175 cm results in ranges of 14.5 cm and 9.3 cm for turn angle and BMI respectively. Those values represent the overall range that the fore–aft foot position will vary (over the range of observed data) and potentially provides a more meaningful comparison between those two regressors.

The parameters of the final step (X_3, Y_3 and q_3) are moderately well predicted by the test and anthropometric variables. However, the relatively large RMSE values associated with X_3 (0.07) and Y_3 (0.09) suggest that the variation in the placement of the third step is fairly large. The final step length Y_3 fit model includes stature as a predictor, suggesting that linearly normalising by stature may not be sufficient to adequately account for population anthropometric effects. However, turn angle dominates the relative importance within the overall fit model of Y_3, with the stature range only affecting the Y_3 variable by approximately 25% of the range produced by turn angle. BMI is included as a variable in the X_3 and q_3 regressions, with larger BMI individuals tending to have larger step widths and larger external rotations.

4. Discussion

This study was conducted to determine the potential effects of turn angle, object mass and anthropometrics on foot placements for two-handed lifting tasks. A quantitative method (Q-TRACS) was developed to describe the pattern of foot placements observed in the data. A regression analysis of the factors affecting the foot placements was conducted for the most frequently observed stepping behaviour. The principal observations from this study are as follows:

- A small number of stepping behaviours (five) accounted for a large percentage (approximately 70%) of the observed object-pickup strategies.
- Turn angle was the primary determinant of the lateral placement of the lead foot for the most frequently observed stepping behaviour.
- The fore–aft placement of the lead foot of the same stepping behaviour is influenced by turn angle and BMI (adjusted R^2 of 0.21). The regression model for this parameter resulted in the lowest observed RMSE among step parameters.
- Turn angle strongly influences the orientation of the terminal stance lead foot for the analysed behaviours (R^2 of 0.53).

Although turn angle was observed to significantly affect the lateral placements (i.e. step width) and orientation of the feet at the time of load transfer, the fore–aft foot locations were also affected but to a lesser degree. Considered independently, object mass (scaled by body mass) did not significantly affect any of the stepping parameters. However, object mass did enter into the step-wise regression analysis as a significant predictor for final step orientation.

The lack of a meaningful relationship between object mass and foot position may be attributed to the analysis being conducted for a single stepping behaviour. Object mass may have affected behaviour selection, rather than affecting the foot placements within the behaviour. Analysis within another stepping behaviour may result in a more observable relationship with stepping variables for the ranges of object masses used here. The limitations of the trial conditions used in the ANOVA precluded the examination of any potential interaction between turn angle and object mass, or a more detailed examination of the relationship between object mass and behaviour selection.

One important observation from this study is that the foot placements associated with picking up objects are significantly affected by the direction in which the worker will proceed following the load transfer. For the most frequently observed behaviour, turn angle affected all the lateral step distance measures, the foot orientation parameters and some fore–aft step distance measures over the three steps necessary to pick up the load and change the direction of progression. Under these conditions, increasing the turn angle from 20° to 180° results in the lead foot rotating approximately 50° toward the direction of the turn. The change in orientation of the lead foot is accompanied by a lateral shift of the same foot away from the direction of the turn, which is equivalent to 0.15*stature (about a 26 cm shift for a 175-cm-tall individual).

After normalisation by stature, the length of the step prior to the stance at the time of load transfer is not well predicted by any of the task or anthropometric measures. Although several significant relationships were observed, the overall model fit was poor and the RMSE remained large. However, the same measure for the step following the pickup was better predicted, with significant relationships for turn angle and stature being demonstrated. This apparent discrepancy may be attributed to the contribution of each of those steps toward positioning the body and, more specifically, how participants transitioned between nominal walking to lifting the object. For example, the final step length of the behaviour (following the pickup) is the first in a sequence of steps along a new direction of progression. Large changes in this step length do not produce important changes in the distance to the next target, measured as a percentage of the total distance to the target. However, the first step length directly affects the placement of the lead foot, which is significantly affected by the task conditions and had the lowest RMSE of all the prediction models. This suggests that the lead foot placement at object pickup is the primary factor, serving as a guide to foot placement prior to object manipulation, and that the step lengths following object manipulation may be altered to accommodate the previous placement of the lead foot in the desired location. One question that remains is whether the final step length absorbs all the residual distance to allow the lead foot to be in a certain location, or if that distance is aggregated over a number of the previous steps.

4.1. Limitations

The most frequently observed stepping behaviour (and the one analysed in detail) across all the test conditions was the split-stance, three-step behaviour with the contralateral foot as the lead foot. However, the prevalence of the contralateral lead foot behaviours may have been over-represented due to the experimental protocol. The same distance between the pickup tower and the start location was used for each trial for a particular subject. Additionally, the subjects were allowed to choose which leg to start stepping with at the beginning of each trial. Subjects may have selected the leg that would facilitate a terminal stance with the contralateral limb as the lead foot. Although this strategy supports the hypothesis that certain stepping behaviour patterns are preferred over others, operators performing multiple object transfers in sequence may not have the same flexibility and would therefore be required to select another stepping behaviour. However, the contralateral lead foot behaviour was the most frequently observed stepping behaviour across all the different trial conditions presented herein and was also the most commonly observed in an industrial setting (Wagner *et al.* 2009).

The present study was conducted in a laboratory environment with two-handed loads that are not representative of many of the hand–object coupling requirements in an industrial setting. Additionally, the load placement in the laboratory experiment was minimally constrained and minimally obstructed by other objects. However, comparison with the stepping behaviours observed in an industrial setting (Wagner *et al.* 2009) suggests that the set of stepping behaviours observed in this study are consistent with those observed in an assembly plant. Of more significant concern is the robustness of these results to the manipulation of objects substantially heavier than the ones tested in this study. The heaviest two-handed load in the laboratory was 13.61 kg, but Wagner *et al.* (2009) revealed many operators lifting loads in excess of 30 kg. Lifts with heavier loads are more likely to be the subject of ergonomic analysis than tasks with lighter loads. Further research is necessary to validate the current findings for heavier loads.

The experimental protocol did not explicitly control which stepping behaviour a participant used or the speed at which the load transfer was performed. Although all the transfer trials collected were completed within a 12-s timeframe, which bounded the upper end of duration used by each participant, no such constraint was imposed to define a minimum transfer trial duration. It has been previously shown that lifting speed significantly affects the flexion/extension moment at the low back (Buseck *et al.* 1988, Tsuang *et al.* 1992, Lavender *et al.* 2003) during sagittal plane lifts utilising parallel stance. Although the Q-TRACS parameterisation encompasses a temporal aspect with the heel/toe lift/contact times, the interaction effect of speed on the foot positions was assumed to be secondary to the anthropometric and task factors considered here and not included in this analysis. This assumption can be partially evaluated by assessing the variance of speed (or overall time to complete each transfer trial) used by the participants in the data for the one-step behaviour. For self-selected lifts, Hooper *et al.* (1998) proposed ‘an inherent “timing mechanism” that governs lifting speed when not deliberately controlled’, suggesting that lifting speed may not greatly vary for self-paced movements. Additionally, the analysis presented in this paper focused on the single most prevalent behaviour observed. Large effects of speed on foot positions would likely first manifest as a change in overall stepping behaviour, with a smaller effect being observed within a single behaviour. The exclusion of speed from the presented regression models does not influence the validity of those results. If a component of speed would enter as a significant regressor for predicting the spatial variables previously described, the resulting models would account for additional variance in the data and only improve the current predictive capacity of the models developed.

Another restriction on these findings pertains to the subject pool recruited for this laboratory study. The participants were recruited from the college student population and none of subjects had significant prior occupational manual material handling experience. However, the results presented herein may still be applicable to experienced operators for similar lifting transfer tasks. A comparison of the stepping strategies used by experienced operators (Wagner *et al.* 2009) and the participants in the present study revealed similar trends in the most frequently observed behavioural preference. Additionally, the support foot during terminal stance of the most frequently observed stepping behaviour was significantly oriented toward the delivery location, an attribute associated with experienced lifters (Authier *et al.* 1996). A 'cross-over' step behaviour associated with experienced lifters (Delisle *et al.* 1999) was also observed in the current study with lower frequency. Although experience has been shown to affect lifting strategy for short distance transfers (Mital 1987, Patterson *et al.* 1987, Gagnon *et al.* 1996), the same trends may not be as important for transfers over larger distances. The potential benefit in balance suggested by Authier *et al.* (1996), resulting in experienced operators limiting the amount of pivoting while carrying the load, may not be applicable for transfer distances that cannot be accomplished in one single motion. Additionally, if used in conjunction with a whole-body model for potential design evaluations, foot placement strategies used by inexperienced lifters would result in an overestimation of traditional ergonomic stressors (e.g. low-back moment; Patterson *et al.* 1987, Gagnon *et al.* 1996) and introduce an additional safety factor for reducing potential hazardous lifting tasks.

4.2. Applications

Biomechanical analyses of materials handling tasks using human figure models, such as Jack (Siemens) or Safework (Dassault Systemes), require prediction of whole-body postures, including foot placements. The findings of this study are also directly applicable to work-cell layout, particularly with regard to the required floor space necessary for operators to perform the stepping behaviour presented in detail herein. Combined with estimates of nominal gait-step length models available in the literature (Grieve and Gear 1966, Macellari *et al.* 1999, Stolze *et al.* 2000, Samson *et al.* 2001) and additional models for predicting the temporal variables of the QTRACS parameterisation, the work here can be used to define travel distances that may facilitate the selection of preferred stepping behaviours that would minimise the total number of steps and time required to perform a load transfer task.

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