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A Task-Based Stepping Behavior Model for Digital Human Models

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ABSTRACT

Cyclical stepping (gait) has been studied extensively. Some of these results are reflected in the straight and curved path step-following algorithms in commercial digital human modeling (DHM) implementations. With the aid of these algorithms, DHM users define start, intermediate, and end path points and the software generates a walking-like motion along the path. Most of these algorithms have substantial limitations, among them that the figures exhibit "foot skate," meaning that the kinematic constraint of foot contact with the ground is not respected. Turning is accomplished by pivoting the entire figure, rather than through realistic lower-extremity motions. The simulation of the non-cyclical stepping motions accompanying manual material handling pickup and delivery tasks requires manual manikin manipulation. This paper proposes a paradigm for the simulation of stepping behavior in digital human models based on a model of foot placements and motions. Cyclical and non-cyclical transition stepping behaviors are handled with the same structure, allowing for smooth transitions between gait and non-cyclical behaviors. The model is based on a laboratory experiment in which participants used one or both hands to move heavy and light loads between shelves located in various positions one to five steps apart. The data were used to develop a model of the transition stepping that occurs at load pickup and delivery.

INTRODUCTION

Human walking and stepping are not simulated well by commercial digital human modeling (DHM) tools. Many of the current commercial DHM applications rely on the playback of prescribed joint-angle trajectories to mimic a walking-like motion while moving the pelvis of the human figure at a prescribed velocity along a defined path. This approach leads to visual anomalies during the motion, the most obvious known as "foot-skate", which occurs because the kinematic constraint between the foot and the ground is not respected. Turning and more complex foot behaviors are not handled at the same level of abstraction and can only be reproduced through time-consuming key-frame animation. Most current DHM implementations turn the human figure by rotating the manikin in place about a vertical line descending through the pelvis without having the feet take a step. Although path following algorithms and cyclical stepping have been well studied (Winter 1995, Winter 1987), conventional methods to represent human walking (i.e. joint angle profiles through time) are not readily adapted toward DHM implementation of turns, the kinematics of which vary widely depending on the task.

The stepping associated with turning and with upper-body materials-handling actions is of greater interest for ergonomics analysis than cyclical gait. Twenty percent of all steps taken by the general population involve turns (Sedgeman 1994) and the actual percentage of steps involved in turns for the ergonomic tasks being addressed may actually be higher. Moreover, the time periods during an industrial workers' job cycle that are of greatest interest to the ergonomist are often those in which a load is picked up or placed, actions that are often accompanied by a transition stepping pattern. The steps taken during a turn also represent a higher risk over other cyclical walking steps. Individuals who fall during a turn, as opposed to a fall during linear walking, are eight times more likely to experience a fracture (Cumming and Klineberg 1994).

Visually realistic turns in DHM simulations are currently produced by playing back motion-capture data, but this approach is not a general-purpose solution for ergonomics analysis. The resulting data are applicable to a single figure and environment geometry. Although methods have been developed to map motion capture data to other figures and to modify the environmental constraints over a limited range (Park et al. 2005), the very large range of possible task and workstation geometries makes the motion-library approach impractical for developing a robust simulation of a standing operator.

A new approach to the simulation of human stepping motions has been developed to address this important area of human motion simulation. The aim of this work is to simulate the stepping motions of the lower extremities for stepping behaviors more complex than walking, with walking as a special case. The new method is demonstrated on pickup and delivery transition behaviors observed during manual material handling transfer tasks.

The feet are modeled as end effectors on kinematic chains terminating at the pelvis. Foot placements and pelvis trajectories are defined as constraints and a behavior-based analytical inverse kinematics approach is used to calculate lower limb positions. This approach is being developed as part of the HUMOSIM ergonomics framework, a comprehensive approach to human motion simulation for ergonomic analysis. This paper presents two components of the framework that address foot placement and motion for materials handling tasks.

METHODS

FACILITY AND TEST CONDITIONS

The human motion data used to develop the new simulation approach were gathered in the Human Motion Simulation (HUMOSIM) laboratory at the University of Michigan as part of a larger experiment. Participants moved boxes and cylindrical objects with a range of weights between pickup and delivery locations while their whole-body motions were recorded. Testing was conducted with low, middle, and high pickup and delivery shelves scaled to participant stature. By varying the tower and participant start locations, the approach and delivery azimuths and delivery distance can be varied. Delivery tower and start location distance to the pickup tower were scaled with step transition distances taken during preliminary trials. Figure 1 shows a participant in the test facility.

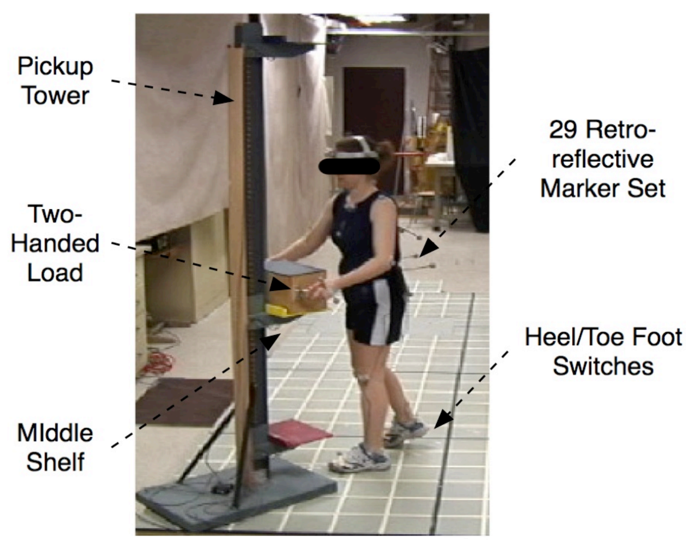

Figure 1. Participant in the test facility, showing pickup tower, two-handed load, and motion capture hardware.

A representative pickup transfer is shown in Figure 2. Participants were asked to approach a load on a shelf from 3-4 steps away, pick up the load, transfer it to another shelf 1-5 steps away, and return to the initial start position. The progression in Figure 2 depicts the participant (1) approaching the pickup location along an approach vector of -135 degrees; (2) at the instance of pickup in a terminal posture; (3) the first step after load pickup along the departure azimuth toward the delivery tower; (4) along the departure azimuth in the double support phase of a gait cycle.

Three start and eight delivery tower locations were defined with respect to the pickup tower location for each subject. The start and shelf tower locations and the associated one and two-handed conditions for each configuration are graphically depicted in Figure 3. One-handed conditions include left and right-handed transfers. Three one-handed and three two-handed loads were tested. Vertical cylinders with a diameter of 7.62 cm were used for the one-handed loads and horizontal cylindrical handles with diameters of 3.81 cm were used for the two-handed totes. The light, medium, and heavy one-handed and two-handed loads were fixed at 0.50, 2.27, 4.54, 1.0, 4.54, and 13.61 kg respectively. Medium one-handed and two-handed weights were transferred between the middle pickup and delivery shelves for all the configurations shown in Figure 3.

Light and heavy load weight and low and high shelf height conditions were chosen to investigate pickup and delivery height and load weight effects. Low, middle, and high pickup and delivery shelf heights were scaled to 0.15, 0.53, and 0.9 times subject stature. For low and middle shelf pickup and deliveries, the higher shelves were raised to not interfere with the transfer motion. Each participant performed the same set of test conditions. Test conditions were blocked within tower configuration to facilitate timely data collection and trials were randomly assigned within each block.

Data were obtained from 10 male and 10 female paid participants: mean [SD]: age: 20.7 [1.34] years and 23.9 [5.34] years; stature: 181.1 [9.3] cm and 167.5 [6.8] cm; BMI: 25.43 [4.12] kg/m^2 and 21.55 [2.63] kg/m^2. The protocol was approved by an institutional review board, and all subjects provided written, informed consent.

MOTION CAPTURE

A six-camera Qualisys Proreflex 240-MCU optical based motion tracking system was used to capture kinematic data. Kinematic data were sampled at 50 Hz. Foot switches affixed to the ball and heel of the foot inside the shoe of the participant were used to collect heel and toe ground contact times. Two AMTI force plates were used near the pickup and delivery towers to quantify balance related issues during those transfer phases. Pressure switches on each shelf were sampled to determine the instance of pickup and delivery. All analog signals were sampled at 500 Hz.

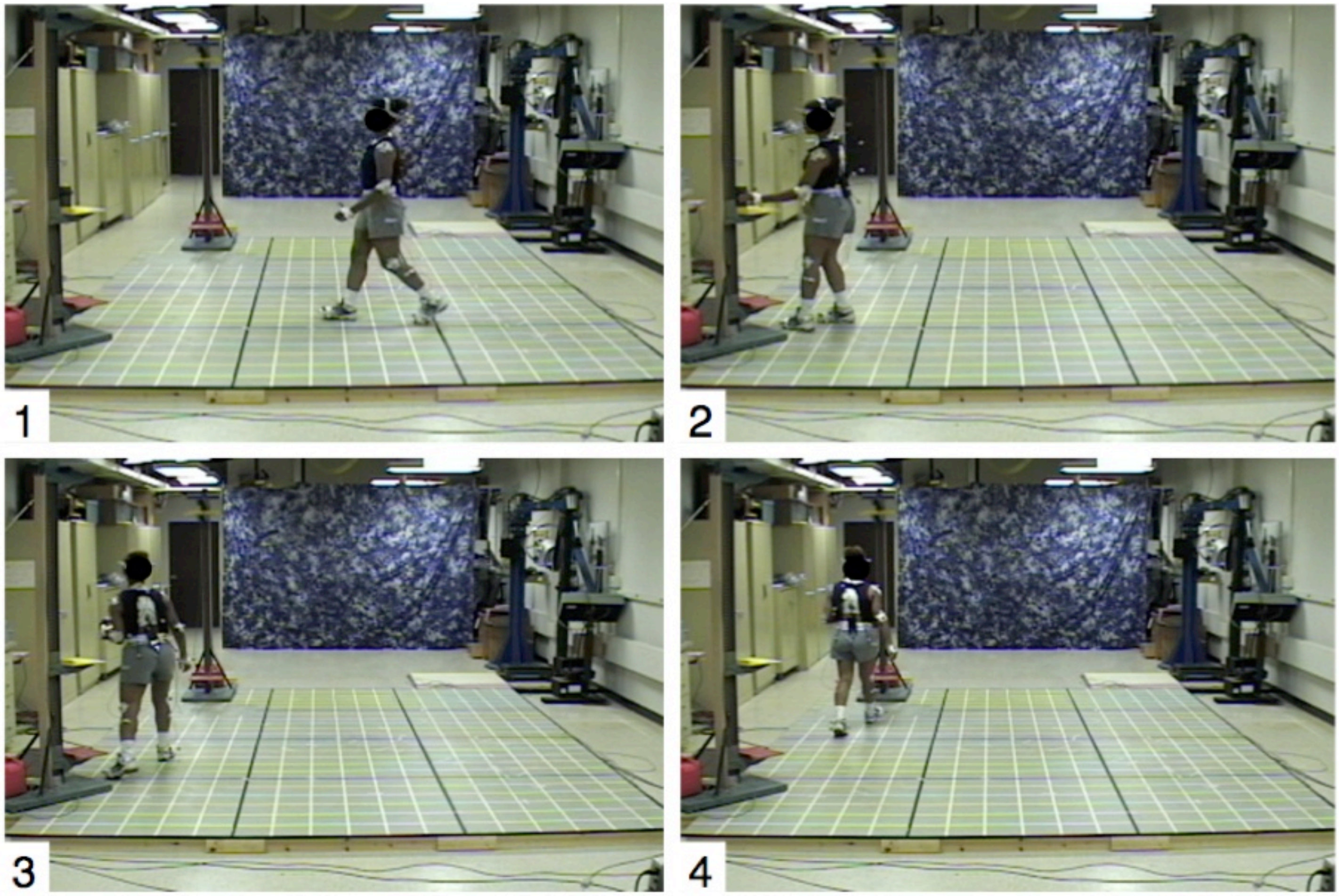

Figure 2. Representative step progression for a pickup transition behavior used during the laboratory experiment (1-4). The transition behavior is encompassed in 2 and 3. Defined measures: approach angle, -135 degrees; departure angle, 135 degrees; pickup height, 0.87 m; load weight, 2.27 kg; left hand.

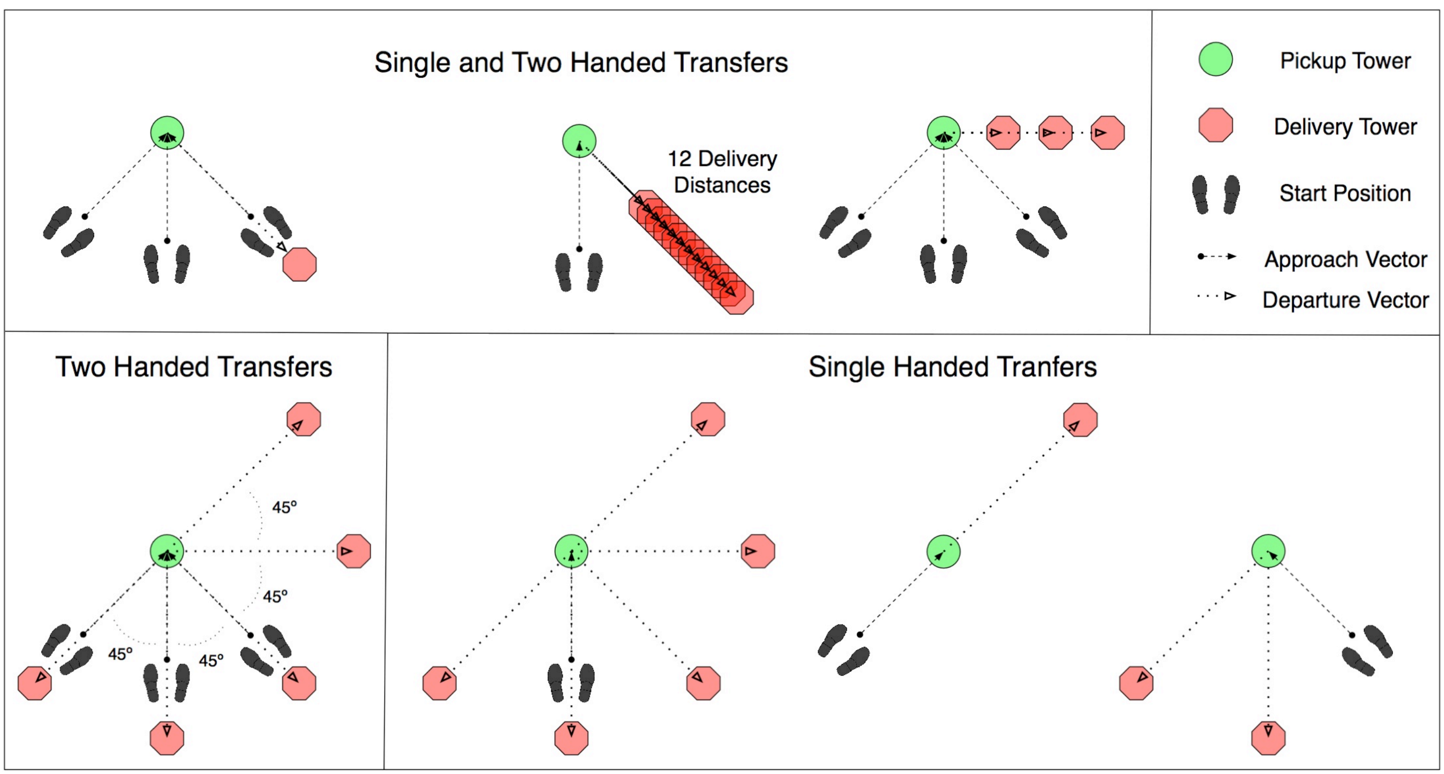

Figure 3. Experiment start and delivery conditions. Distances are not to scale.

RESULTS

TRANSITION STEPPING CLASSIFICATION

An important observation of this research is that a large majority of foot behaviors in manual materials handling (MMH) tasks are consistent with a small number of basic patterns. As part of the process of developing a new predictive model for foot behaviors, a classification system or taxonomy of foot behaviors was developed, known as TRACS (Transition Classification System). Twelve unique right-turn stepping behaviors for the taxonomy were generated from laboratory and industry behavior observations. Each TRACS behavior includes the relative foot positions (i.e. feet together, left foot in front, right foot in front, etc.) and the relative heel and toe ground contact (graphically depicted by a shaded region) throughout the pickup/delivery task. Figure 4 shows one common behavior. In this case, the simulated human initiates a rightward turn by lifting and pivoting the left foot, which has been placed in a trailing position. The right foot is then lifted and placed along the line of departure from the pickup station.

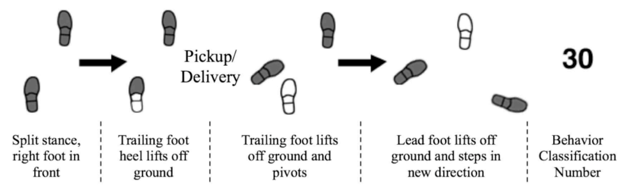

Figure 4. Example of a transition-stepping behavior used in the Transition Classification System (TRACS). The motion proceeds from left to right. Shaded foot regions symbolize contact with the ground; unshaded areas symbolize no contact.

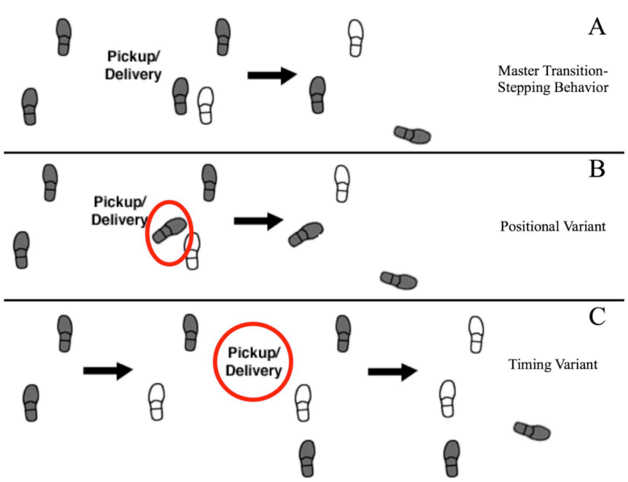

Figure 5. Example of a TRACS behavior and two TRACS variants. A) Master TRACS behavior, B) Orientation variant, C) Pickup/Delivery timing variant.

Each TRACS behavior includes the stance used at the time of pickup or delivery through the steps prior to a return to cyclical stepping. By modifying foot orientation, pickup/delivery timing, and/or the sequence of foot progressions, multiple variants for each behavior can be produced (Figure 5). Forty-nine unique TRACS variants have been explicitly identified. The right-turn TRACS behaviors are mirrored to generate equivalent left-turn behaviors.

TRANSITION BEHAVIOR FREQUENCY

Transition behaviors at the time of load pickup were analyzed in the data from the laboratory study. Results from a subset of 96 pickup transfers moving the medium load from the middle pickup shelf to the middle delivery shelf for one and two-handed conditions spanning 3 approach angles and 5 departure angles are presented. Four TRACS behaviors (nine TRACS variants) accounted for over 90% of the observed step progressions (Figure 6).

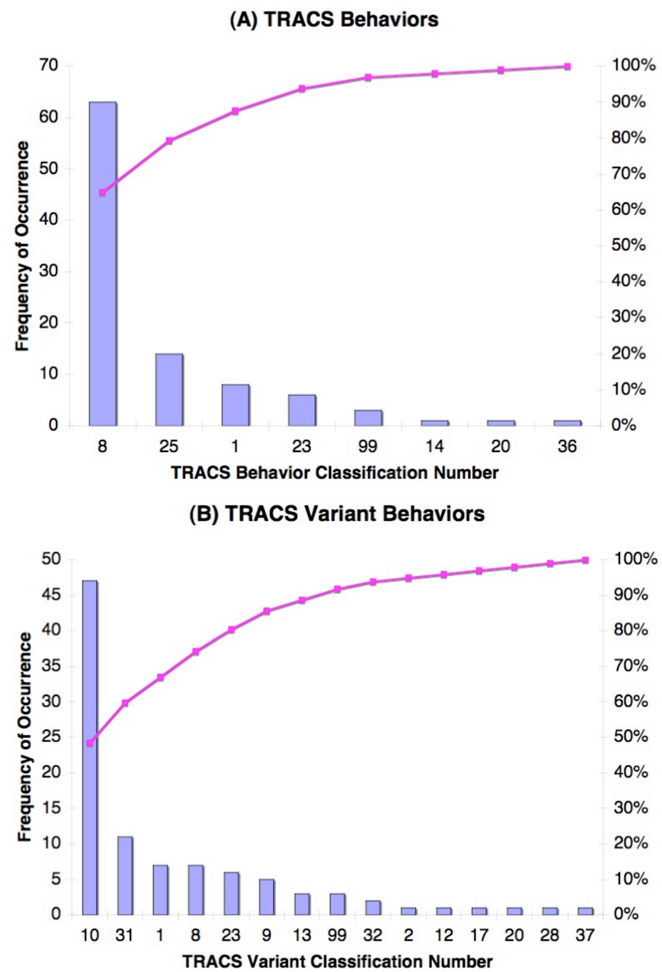

Figure 6. Cumulative distribution for 96 transition-stepping behaviors observed in the laboratory. A) TRACS Behaviors. B) TRACS variants.

TRACS behaviors 8, 25, 1, and 23 were observed most frequently (Figure 7). Behavior 8 defines a split or single leg stance with the left foot as the lead at the time of pickup/delivery. Behavior 25 defines a split stance with the right foot as the lead at the time of pickup/delivery and also defines an orientation change of trailing leg prior to a step with the lead foot in the new direction. Behavior 1 defines the feet side-by-side at the instance of pickup/delivery followed by a step with the right foot along the departure vector. Behavior 23 defines a split stance with the right foot as the lead at the time of pickup/delivery.

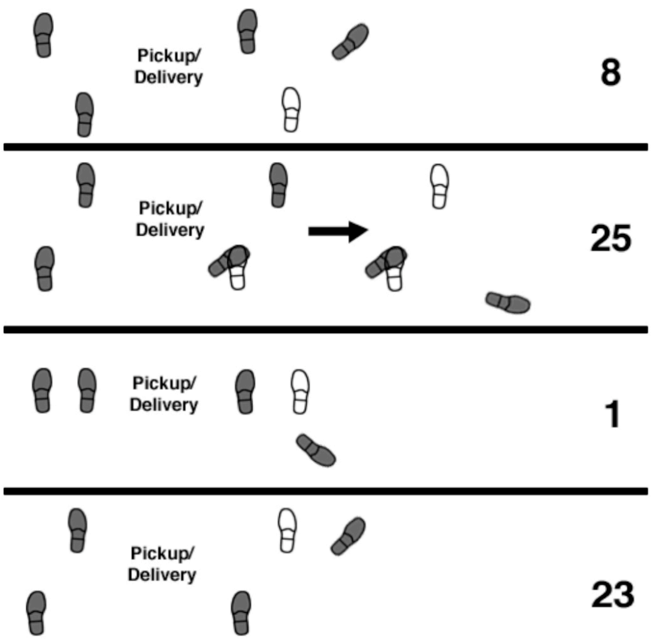

Figure 7. The four most frequently observed transition-stepping behaviors (ordered top to bottom) accounted for over 90% of the transitions observed in the selected laboratory trials.

PARAMETERIZATION OF TRANSITION STEPPING

Each foot behavior in the TRACS taxonomy is a unique set of relative foot positions and timed foot events (heel up, toe up, heel down, toe down). A footstep in TRACS describes the contact of a foot with the floor, the stance interval, and the departure of the foot from the floor. Each footstep is represented by the vector $\boldsymbol{F}$, where $\boldsymbol{F}$ is given by:

$$\boldsymbol{F} = [f,\ T_x,\ T_y,\ \theta,\ t_{hd},\ t_{td},\ t_{hu},\ t_{tu}\ ]^T$$

where f is the foot (*right* or *left*); T_x, T_y is the location of the toe landmark in a coordinate system established by the pickup/delivery location; θ is the orientation of the foot in this coordinate system; and the t_{nn} are the times of the heel-down, toe-down, heel-up, and toe-up events relative to the pickup/delivery time. Each instance of a TRACS behavior is represented by a behavior matrix

$$\boldsymbol{B} = [\boldsymbol{F}_1,\ \boldsymbol{F}_2,\ \ldots\ ,\ \boldsymbol{F}_n]$$

where n is the number of non-gait steps in the behavior. B can be partitioned into right and left-foot components,

$$\boldsymbol{B} = [\boldsymbol{B}_R,\ \boldsymbol{B}_L]$$

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

TRANSITION STEPPING MODEL

Based on the results of the laboratory investigation, a new modeling concept has been developed to predict the foot motions associated with manual materials handling tasks. Figure 8 graphically depicts the information flow in the Transition-Stepping and Timing (TRANSIT) model. A TRACS behavior is selected through a discrete variable selection technique based on the task parameters and subject characteristics. For example, a particular combination of task and subject variables might result in the selection of TRACS behavior 25. Each TRACS behavior has a defined number of steps for the right and left foot, so that the number of columns of the $\boldsymbol{B}$ matrix is defined.

The footstep vectors $\boldsymbol{F}_i$ for the behavior matrix $\boldsymbol{B}$ are then predicted from subject characteristics with continuous statistical models fitted using data from participants performing tasks using the specified behavior. A method similar to that used for predicting terminal foot placements (Wagner et al. 2004) is used to predict the positional parameters (T_x, T_y, θ) for each step. A separate model then assigns the timing profile (t_{hd}, t_{td}, t_{hu}, t_{tu}) for each step of the TRACS behavior to generate a TRACS variant. Once the transition foot placements are defined, approach and departure footprints are defined via a cyclical stepping module.

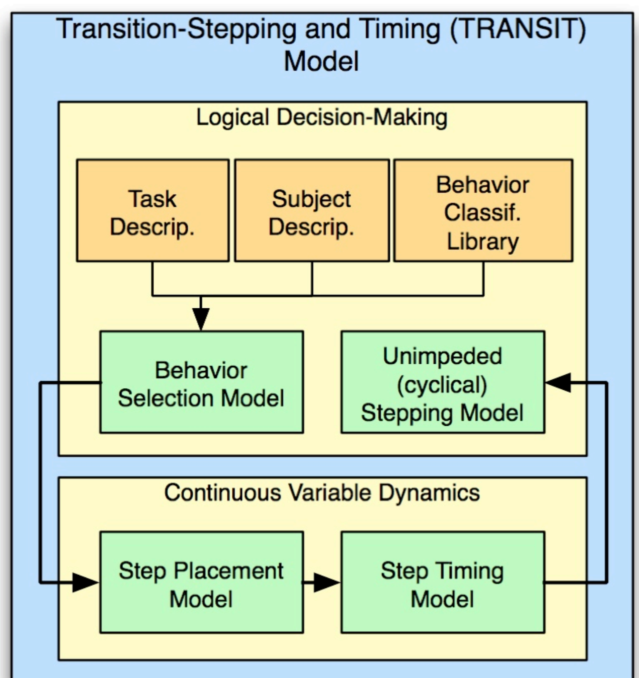

Figure 8. Transition-Stepping and Timing (TRANSIT) model. Flow diagram of modules comprising the TRANSIT model.

The step placement model, which defines the positions and orientations of the behavior footprints, requires that each classification behavior can be applied to a wide variety of task situations. For example, classification behavior 10 (Figure 9) depicts a split stance during the pickup/delivery, which is followed by a step with the trailing leg in the direction of departure. The split stance foot positions (T_X, T_Y), for both the lead leg and trailing leg are defined based on the approach vector and pickup/delivery position. The lateral placement of the foot (T_X) is directed perpendicular to the approach vector while the fore-aft placement of the foot (T_Y) lies parallel with the approach vector (Figure 10).

The calculation of ***F*** is facilitated by a reparameterization using the approach and departure vectors. For example, in transition behavior 10, changes in the departure vector angle change the effective step length (and width) between the lead foot and the final step. One approach to the reparameterization for this behavior is to use selected spatial parameters defined for non-linear walking (Huxham 2005). This method defines the fore-aft foot position as the stride length (T_{Y2}) and the lateral placement as the step width (T_{X2}). These measures are more meaningful than the equivalent counterparts of T_X and T_Y displaced along the departure vector as they are directly related to the previous steps taken.

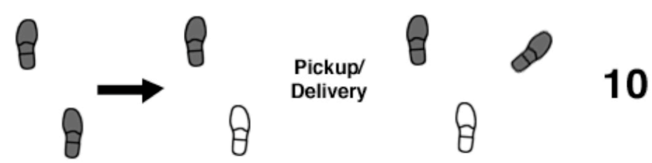

Figure 9. Transition Behavior Classification 10.

The angular rotation of the foot (θ) is parameterized in the same manner for all TRACS behaviors. The angle is referenced from the orientation of the adjusted approach/departure reference frame. This convention allows for the comparison of pivot angles from different TRACS behaviors when a foot pivot is used to reorient the body.

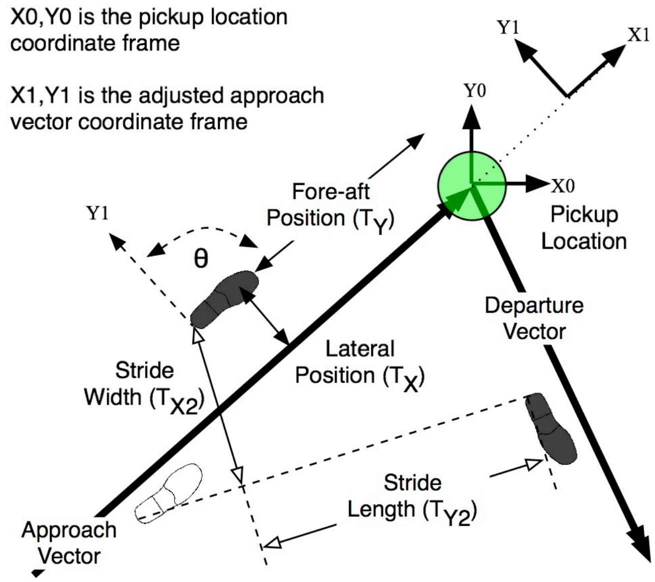

Figure 10. Parameterization for TRACS Behavior 10.

Parameterization of individual foot placements for different behaviors follows a similar approach as described for behavior 10. The stance prior to pickup is derived from a global reference frame rotated to be aligned with the approach vector. Subsequent steps are referenced off the initial stance to maintain appropriate measures of step length and width. Pre-orientation and pivot behaviors are handled as changes in the foot angle, which is referenced from the adjusted pickup/delivery axes.

Representative parameter values (reported in the pickup/delivery reference frame) for two observed behaviors are listed in Table 1. NULL values in the table indicate that the measure is not required to characterize the observed behavior. A representative 4-step gait cycle is defined from literature values and presented in the same parameterized form (Whittle 2002).

Table 1. Representative values for two selected TRACS behaviors (1-2), and a nominal gait cycle (3).

F_n	f (left/right)	T_X (m)	T_Y (m)	θ (degrees)	t_{hd} heel up time (s)	t_{td} toe down time (s)	t_{hu} heel up time (s)	t_{tu} toe up time (s)
1. Classification Behavior 28, Pickup location: [-0.6211, 1.7833, 0.3328] m Pickup time: 4.65 sec. Right turn								
F_1	left	-0.6423	1.295	-15	3.82	3.92	4.24	Null
F_2	right	-0.3896	1.487	-15.9	4.16	4.18	5	4.96
F_3	left	-0.6122	1.381	-59	4.92	Null	5.28	5.48
F_4	right	-0.1019	0.7835	-136.7	5.42	5.62	5.88	6.12
2. Classification Behavior 10, Pickup location: [1.7926, -0.2071, 1.0762] m Pickup time: 4.72 sec. Left turn								
F_1	right	0.8546	0.5762	-144.5	3.28	3.36	3.44	3.92
F_2	left	1.411	0.1637	-149.6	3.82	3.9	4.26	4.96
F_3	right	0.8879	-0.2277	141.9	4.82	4.9	5.06	5.52
3. Representative Gait Cycle Male, 1.045 sec cycle time (18-49 age group nominal value)								
F_1	left	0	0	-8	0	0.125	0.334	0.606
F_2	right	0	.66	8	0.523	0.543	0.857	1.129
F_3	left	0	1.32	-8	1.045	1.17	1.379	1.651
F_4	right	0	1.98	8	1.567	1.588	1.902	2.174

DISCUSSION

A new approach to the analysis and simulation of foot behaviors in manual materials handling tasks has been developed. A taxonomy of foot behaviors developed from observations of task performance (TRACS) showed good utility for categorizing behaviors. Data from a laboratory study illustrated that four behaviors accounted for over 90% of the observed foot behaviors.

TRACS is used as part of the new TRANSIT model to predict foot behaviors. Based on task and human characteristics, the model selects a TRACS behavior, then scales the foot placements with respect to time, location, and orientation using statistical models developed from the laboratory study.

A person can perform a task with a wide variety of different foot movement patterns, but the data from the current study suggest that for tasks where an individual has an accurate knowledge of the environment, particularly for well-learned and practiced jobs, there exists a meaningful consistency of stepping behaviors within and between individuals. Furthermore, these stepping progressions can be represented by a concise set of scalable behaviors that are a significant subset of those observed for every day activity.

Although the current model represents a substantial advance in the prediction of task-oriented foot motions, the application of the current model is limited in several ways. The transition behaviors presented here are from a laboratory study with a small sample size and a population of young fit participants. Participants were required to wear motion capture equipment throughout the experiment. Each transfer objects had handles (two-handed) or rubber hand rests (one-handed) to promote good coupling. The laboratory environment contained only the pickup and delivery towers as obstacles. Similar ideal conditions may not exist in industrial settings and may affect the applicability of the results. The findings from this laboratory work will be validated by comparison with foot movements observed in an auto assembly plant.

An advantage to the parameterization described above and how foot placements can be used to drive whole body standing motion is the flexibility of the modeling framework. Applications for driving digital human models with foot placements are not limited to workcell transfer tasks or even manual material handling. The stepping behaviors during an industrial line-tracking task could be modeled using a similar approach as described here. The parameterization could be expanded to include a vertical component for both the heel and toe and walking on a ramp or ascending a staircase could be driven with the same structure. Any stepping behavior that can be quantified with heel and toe positions and ground contact and lift times can be used with the framework proposed here to drive whole body stepping motions.

Accurate representation of foot placements and timing for non-stationary standing tasks can be used to influence the design of the work layout. The necessary floor space to accommodate a single or set of nominal transition behaviors can be used as a design criterion for workcell layout. Footprints of multiple workers can also be used to simulate worker movement for a defined set of tasks. Traffic bottlenecks, high traffic areas, part transfer and workflow times, and the minimum floor space necessary to accommodate multiple workers are a few of the metrics that can be assessed with an accurate representation of worker foot placements.

Future work is focused on developing the necessary models to provide robust simulation of industrial workcell activities. Modeling the scaling of step-size and understanding how participants choose step-size to traverse a given distance will be addressed along with the effects pickup and delivery height have on behavior selection. The outcome of this work will be dramatic improvements in the ability of DHM software to simulate lower-extremity movements in industrial tasks.

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REFERENCES

1. Ayoub, M. M. (1998). A 2-D simulation model for lifting activities. *Computers & Industrial Engineering,* **35**(3-4): 619-622.
2. Ayoub, M. M. and C. J. Lin (1995). Biomechanics of manual material handling through simulation: Computational aspects. *Computers & Industrial Engineering,* **29**(1-4): 427-431
3. Badler, N.I., Allbeck, J., et al. (2005). New Behavioral Paradigms for Virtual Human Models. Technical Paper 2005-01-2689. *SAE International,* Warrendale, PA.
4. Badler, Norman I. *Simulating Humans: Computer Graphics Animation and Control*. New York: Oxford University Press, 1993.
5. 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.
6. Branicky, M.S. (1999). Behavioral Programming. *AAAI Spring Symposium Technical Report: Hybrid Systems and AI*, 265-270.
7. Burgess-Limerick, R. and B. Abernethy (1998). Effect of load distance on self-selected manual lifting technique. *International Journal of Industrial Ergonomics,* **22**, 367-372.
8. Chaffin, Don. (2005). Improving Digital Human Modelling for Proactive Ergonomics in Design. *Ergonomics*, **48**(5), 478-491.
9. Cumming, R.G., and , R.J. Klineberg (1994). Fall Frequency and Characteristics and the Rist of Hip Fractures. *Journal of the American Geriatrics Society,* **42**,774-778.
10. Delisle, A., M. Gagnon, et al. (1996). Load Acceleration and Footstep Strategies in Asymmetrical Lifting and Lowering. *International Journal of Occupational Safety and Ergonomics,* **2**(3): 185-195.
11. Delisle, A., M. Gagnon, et al. (1998). Knee flexion and base of support in asymmetrical handling: effects on the worker's dynamic stability and the moments of the L(5)/S(1) and knee joints. *Clinical Biomechanics (Bristol, Avon),* **13**(7): 506-514.
12. Delisle, A., M. Gagnon, et al. (1999). Kinematic analysis of footstep strategies in asymmetrical lifting and lowering tasks. *International Journal of Industrial Ergonomics,* **23**(5-6): 451-460.
13. Drury, C. G., C.-H. Law, et al. (1982). A survey of industrial box handling. *Human Factors,* **24**(5): 553-565.
14. Dysart, M. J. and J. C. Woldstad (1996). Posture prediction for static sagittal-plane lifting. *Journal of Biomechanics* **29**(10): 1393-7.
15. Gagnon, M., A. Plamondon, et al. (1993). Pivoting with the load. An alternative for protecting the back in asymmetrical lifting. *Spine*,**18**(11): 1515-24.

16. Kollmitzer, J., Oddsson L., et al. (2002). Postural Control During Lifting. *Journal of Biomechanics*, **35**(5), 585-94.
17. Hase, K. and R. B. Stein (1999). Turning strategies during human walking. *Journal of Neurophysiology*, **81**(6): 2914-2922.
18. Inman, Verne, Ralston, Henry, and Todd, Frank. *Human Walking*. Baltimore: Williams & Wilkins, 1981.
19. Park, W., Martin, B.J., Choe, S., Chaffin, D.B., Reed, M.P. (2005). Representing and identifying alternative movement techniques for goal-directed manual tasks. *Journal of Biomechanics*, **38**(3): 519-527.
20. Sedgeman, R., Goldie P., Iansek R. (1994). Development of a measure of turning during walking. *Advancing rehabilitation conference Proceeding,* La Trobe University, 26-31.
21. Wagner, D.W., Reed, M.P., and Chaffin, D.B. (2005). Predicting Foot Positions for Manual Materials Handling Tasks. Technical Paper 2005-01-2681. *SAE International*, Warrendale, PA.
22. Whittle, Michael. *Gait Analysis: An Introduction*. Oxford: Butterworth-Heinemann, 2002.
23. Winter, D. A. (1979). *Biomechanics of human movement.* New York, Wiley.
24. Winter, D. A. (1987). *The biomechanics and motor control of human gait*. Waterloo, Ont., University of Waterloo Press.
25. Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait and Posture*, **3**: 193-214.