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Simulating Complex Automotive Assembly Tasks using the HUMOSIM Framework

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ABSTRACT

Efficient methods for simulating operators performing part handling tasks in manufacturing plants are needed. The simulation of part handling motions is an important step towards the implementation of virtual manufacturing for the purpose of improving worker productivity and reducing injuries in the workplace. However, industrial assembly tasks are often complex and involve multiple interactions between workers and their environment. The purpose of this paper is to present a series of industrial simulations using the Human Motion Simulation Framework developed at the University of Michigan. Three automotive assembly operations spanning scenarios, such as small and large parts, tool use, walking, re-grasping, reaching inside a vehicle, etc. were selected. A conceptual model for describing relationships among task objectives, the environment, parts and tools, as well as worker variability, work methods, motion patterns, and musculoskeletal disorder (MSD) risks is proposed as a structure for conducting the case studies. The conceptual model is implemented using simulation strategies and the HUMOSIM Framework. Analyses demonstrate that the HUMOSIM Framework provides improvements on simulation capabilities over the built-in Jack functionality, such as the prediction of force-exertion posture and stepping motions. But knowledge gaps are also identified for part handling simulations, in particular the prediction of grasping and re-grasping. Methods for integrating part assembly paths generated by other simulation software are also needed.

INTRODUCTION

Work objects, such as tools and parts, should be presented to operators in ways that minimize non-value added work and physical stresses. Ergonomic and productivity issues not identified during virtual assessments must often be identified and corrected at the start of manufacturing, adding cost and delaying production. In some cases, when improvements to best practices are identified, changes are made to the plant floor months or years after a product goes into production. During that time the worker may perform needless non-value added work and experience work-related musculoskeletal disorders (WMSDs), that necessitate medical treatment and time away from work (NRC, 1998). Significant attention is directed toward eliminating non-value added work and WMSDs. Physical mockups, prototypes and user trials require time and money that often are not available. Tools are needed that can be used to predict and simulate how workers interact with work objects (such as reach for, grasp, move, position and use work objects) so that the best work designs can be selected before going into production.

Computerized design tools that can be used to help visualize the workplace, operator, tools and materials are a promising alternative to physical prototypes; however, current human modeling software systems lack the capability to accurately predict many of the motions and postures required to reach, grasp, move, position and use work objects. Designers must use their experience and judgment to manually posture the body

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and hands of human figures to simulate assembly tasks. The simulations can require considerable time and are subject to significant inter and intra subject variations. The Human Motion Simulation Framework (Reed et al. 2006) was developed to provide a means to integrate models and algorithms for motion simulation and ergonomic analysis. To aid in the development and demonstration of the algorithms, a reference implementation has been developed for use in the Jack software system. Given inputs such as the locations of end-effectors (hands, feet, and gaze direction), the HUMOSIM Framework predicts whole body postures and motions using a set of numerical algorithms. Manual posturing is eliminated, improving the speed and repeatability of posturing. The accuracy of predicted postures and motions are grounded in models that are validated by experimental data. The HUMOSIM Framework also provides functionalities such as predicting force-exertion postures for the needs of simulating complex assembly tasks. However, the current HUMOSIM Framework lacks certain functionality required to automatically simulate part handling motions. The gaps need to be identified and resolved.

Currently a number of commercially available automatic assembly path generation software tools are used in manufacturing designs at automotive corporations (such as Kineo Path Planner, see Laumond, 2006). These software tools can quickly generate collision-free paths for parts given design specifications (i.e., start location and final location). However, they do not consider human body physiological constraints such as strength capability to ensure paths are physiologically reasonable for the operator. A vision is to integrate path planning techniques into digital human models for simulation of part handling tasks. Hypothetically, this integration has the advantage of utilizing the current state-of-the-art assembly path planning technique, and greatly reducing the time required to generate realistic dynamic motions.

This study was performed to assess the performance of the current HUMOSIM Framework for predicting accurate postures and motions in assembly tasks. Towards this end, 1) a conceptual model was proposed to describe the relationship between task, workspace, tool and material attributes, worker attributes, postures, motions and forces, and WMSD risk factors; 2) three auto assembly tasks were selected and decomposed into a sequence of motion elements; 3) each motion step was then examined to determine if a model or algorithm is available in the HUMOSIM Framework, or could be identified from the available literature for predicting the corresponding postures, motions and forces; 4) models needed to fill the identified knowledge gaps were then discussed. In addition, the feasibility of integrating assembly path generation with human motion algorithms was evaluated.

METHODS

A CONCEPTUAL MODEL - To simulate part handling tasks, it is necessary to create a structure / framework by which to identify and analyze the parameters and models required for simulation. In the conceptual model (Figure 1), the work content, work object, environment, and workers are work specifications (inputs). The work content is a description of actions that the worker must perform to complete a manufacturing assembly operation. The descriptions are in terms of work-object attribute, e.g., join part A to part B – not in terms of worker attributes, e.g., walk, reach, grasp. The work content does not account for differences in movement patterns that may result from obstructions, part variations, etc. and granularity is adjusted to capture work-object attributes that affect actions required to complete the job (e.g., snap fit/attach threaded fastener).

The work objects (parts, tools) and environment are usually design specifications that can be stored in data management systems, which include information such as object geometries, material, weight, and center of mass.

Based on work content, work object, and environment, the work content descriptions can be broken into a sequence of work methods. The generation of work methods can be accomplished by industrial engineers and is based on experience. Work methods could potentially be created by task scheduling algorithms that have been proposed to allow for high-level task sequence scheduling and execution, such as the Parameterized Action Representation model (Badler et al., 2005) and Task Simulation Builder (Raschke et al., 2005). For example, as suggested by Ianni (1999), a set of worker motions can include Get, Put, Position, Touch, LookAt, UseTool, and Operate. The granularity of the work methods can increase. For example, a Get can be decomposed into a walk, reach, grasp, and move. The motion sequence is then simulated by quantitative motion simulation models, such as the motion algorithms within the HUMOSIM Framework, to obtain postures and motions.

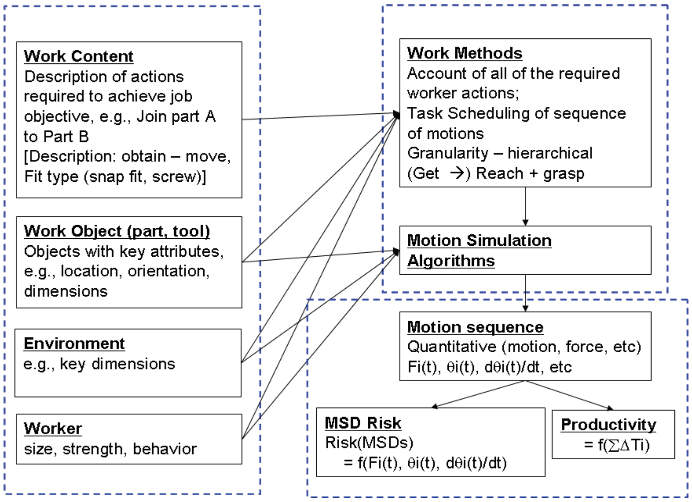


Figure 1. A conceptual model for part handling tasks.

The MSD risks can be then evaluated by epidemiology and biomechanical models as a function of exertion force, posture, and motions. Models for the pathogenesis of WMSDs, such as the one proposed by Armstrong et al. (1993), are useful for identifying the multiple factors that contribute to the development of WMSDs. The productivity, which is another output, is a function of total work time predicted by motion simulations. These two outputs can also serve as objective functions to be optimized for the design specification/work content.

CASE STUDIES - Three automotive assembly operations covering complex scenarios, such as small and large parts, tool use, walking, re-grasping, reaching inside a vehicle, were selected. These case studies are:

- Headlamp installation: Install and secure a headlamp on a truck (two workers are involved). The tasks include: get headlamp assembly from bin, carry it to the truck, position the assembly on the truck, and hold it while a second worker secures it with 3 bolts using a right angle tool.

- Quarter extension secure: Secure rear quarter flare extension to proposed body bracket using a right-angle tool.

- Heater hose insertion: Deep reach into engine compartment with multiple interferences to insert heater hoses with potential body bracing.

The available information for these case studies are the job descriptions, task requirements, and CAD geometries for the work objects in Jack 6.0 software. In addition, plant tours and movies of plant operations were used for validation purposes. Based on the conceptual model, the case studies were conducted using the simulation procedure described below.

SIMULATION PROCEDURE - Given a specific job such as the task of installing a headlamp, the conceptual model gives a structure for describing the key factors that are critical for automatic computer simulations of this job. By referring to the job descriptions, the objectives or work content of this job includes:

1. Join headlamp (in bin) and truck

2. Join 3 bolts to headlamp and truck (secure)

These objectives are goals that must be accomplished in this job. It is necessary to work backwards to determine the required work methods for a given work content and then decompose the work methods until sufficient granularity is achieved to identify the factors that affected the postures, motions and forces. For example, to join the headlamp and truck, the worker must first get the headlamp from bin, then transfer and position it to the truck. To secure the headlamp, a second worker must get and use the tool while the first worker holds the headlamp. The granularity of work methods need to be increased in order to capture variances in the motions. For example, “get headlamp” can be decomposed into “walk to, reach, grasp, and move headlamp”, or can be decomposed into “reach, grasp, and move headlamp” if the headlamp is within worker’s reach envelope. The decomposition depends on the work content and the parameters of work objects, environment, and the worker.

The work objects involved in this job include: truck, headlamp, right-angle tool, and bolts. These work objects have their associated key parameters, such as size, weight, and location. A work object may be associated with many attributes, but not all of them are key parameters that are useful for simulation. The key parameters are selected only if they affect the generation of work methods or serve as inputs for motion simulation models. For example, the location of target object and the location of worker are key parameters since they are useful to determine whether the object is within worker’s reach envelope, thereby determining whether a “walk” motion is required or not. Some key parameters are also inputs needed for quantitative motion simulation models. For example, predicting a reaching motion may require the inputs of part dimensions, locations, orientations, and so on.

It is desirable to be able to automatically generate motion sequence given parameters of work objects, environment, and the worker for a work method. Using “get” motion as an example, without loss of generality, a “get” motion can be decomposed into multiple basic motions / work methods such as: walk (stepping), reach (no object in hand), brace (use 1 hand to support for reach), grasp, move (with object in hand), vision check (head movement), and re-grasp (a series to release, reach, grasp, move to re-orientate the headlamp for secure control). Some basic motions such as bracing may not appear in one “get” task, but may appear in another “get” depending on the environmental conditions. These motions may occur consecutively or concurrently. A simultaneous motion table can be used to organize these motions and describe the work process (Figure 2). To develop a strategy for automated part handling simulation, there are two questions that need to be answered:

- How can an algorithm decompose a given motion and figure out the simultaneous motion table automatically? For example: What is the sequence of the basic motion steps for “get” motion? Is a basic motion step (such as walking/bracing) required or not for a specific “get” motion?

- What models (and parameters) are needed for each of the basic motion steps? Are they available in the HUMOSIM Framework? Or are they reported by other literature?

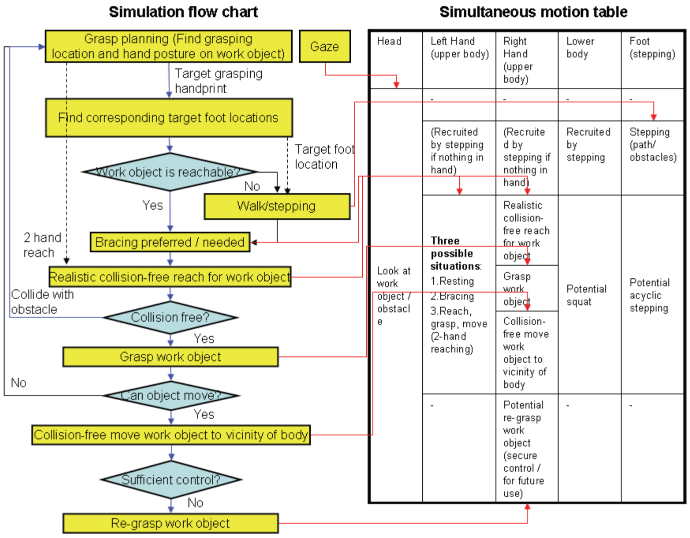


Figure 2. Simulation flow chart and associated simultaneous motion table for "get" motion.

The first question leads to the development of a simulation flow chart as shown in Figure 2. This flow chart serves as a schematic representation of the motion process. There are motion models that directly simulate a specific motion that appears in the simultaneous motion table. There are also processing / planning models that provide inputs to subsequent motion steps. In addition, there are decision rules that determine whether a specific motion is required or not. For example, if the part is not reachable, then walking / stepping is required. The simulation flow chart describes the execution process for a given task.

Given a specific task, the identification of models in the simulation flow chart is based upon examination of steps and assumptions during our case-study simulations. The steps and assumptions made during simulations are carefully recorded. By going through the steps and assumptions, a flow chart is generated. It should be noted that the identified models are specific for the HUMOSIM Framework. For example, since the HUMOSIM Framework requires inputs of end-effectors (hands, feet) to predict whole body motion, it is necessary to have a model that can predict target hand posture on work object. By following the procedure, we can create simulation flow charts for all work methods in the three case studies.

The second question leads to a gap analysis of models. By going through the simulations of various case studies, the simulation steps, assumptions, and flow chart are examined to determine the availability of a required model in the HUMOSIM Framework. For the gaps (unavailable models or models that lack certain capabilities in the HUMOSIM Framework), their availability in commercial software or in reported literature is identified. The required models and gap analysis are summarized in the discussion section.

All motion simulations are generated using the HUMOSIM Framework reference implementation in Jack 6.0 environment. Only simulation results from the first case study, the job of installing a headlamp, are presented in this paper.

RESULTS

Simulation results for the four work methods / steps required to complete the job of headlamp installation are presented in this paper. They are: the first worker gets headlamp from bin; the first worker puts (positions) headlamp to truck; the first worker holds headlamp to maintain fit; and a second worker secures headlamp to truck with 3 bolts. The general simulation steps, assumptions, required models, and results are described. The screenshots of simulated motions are shown.

GET HEADLAMP - As a first step, the HUMOSIM Framework requires inputs of end effectors (target hands / feet) to predict whole body motions. Therefore, an object grasping model, which can automatically predict realizable and stable grasping hand posture on an arbitrary part, is needed. Since this model is not available in the HUMOSIM Framework (a gap), a target hand print is manually specified on the headlamp. The selection of the location and posture of the hand print is dependent on assumptions regarding parameters such as the initial location & orientation of the worker, location & orientation of the headlamp, and geometry of the headlamp. These assumptions are identified as potential inputs to the object grasping model.

As a second step, target foot locations need to be computed from the target hand locations. Then a "reach-ability" model is needed to determine if the worker needs to walk to the target foot locations. If walking is required, the TRANSIT stepping model in the HUMOSIM Framework is used to automatically predict foot placements and realistic whole-body stepping motions (Reed and Wagner, 2007). However, the current TRANSIT stepping model lacks obstruction avoidance to cover the condition when obstructions are on the stepping path. Therefore, it is identified that a walking model is available in the HUMOSIM Framework but it lacks obstruction-avoiding capability.

Thirdly, for this case it was assumed that no bracing is required to get the headlamp but in certain assembly operations bracing might be required. Thus a bracing model is required and currently under development (Jones et al., 2008).

Fourthly, when generating moving motion it is assumed that the worker has sufficient grasping capability and control over the headlamp and that there is no obstruction on the moving path. These assumptions imply factors that need to be considered in a realistic collision-free moving motion model. The current HUMOSIM Framework can predict realistic motions but the prediction is not necessarily collision-free. Therefore, the moving motion model is identified as available but lacking obstruction-avoiding capability.

Lastly, the worker may need to re-grasp the headlamp to securely hold it after picking it up. Thus a data grounded re-grasping model is required to predict such motion. Since a re-grasping model is not available in the HUMOSIM Framework, the target hands for the re-grasping sequence are manually specified in the simulation. The re-grasping motions are generated by the HUMOSIM Framework by reaching to a sequence of target hands. Screenshots captured from the simulation of "get headlamp" work method are presented in Figure 3.

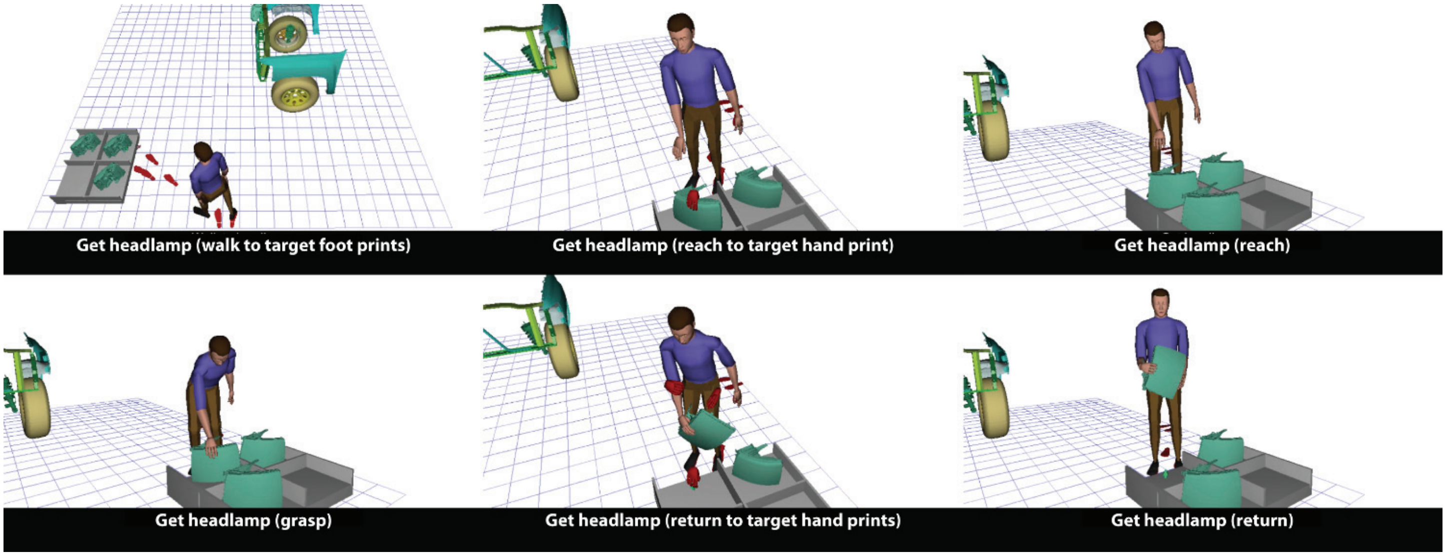


Figure 3. Screenshots captured from simulation results of "get headlamp".

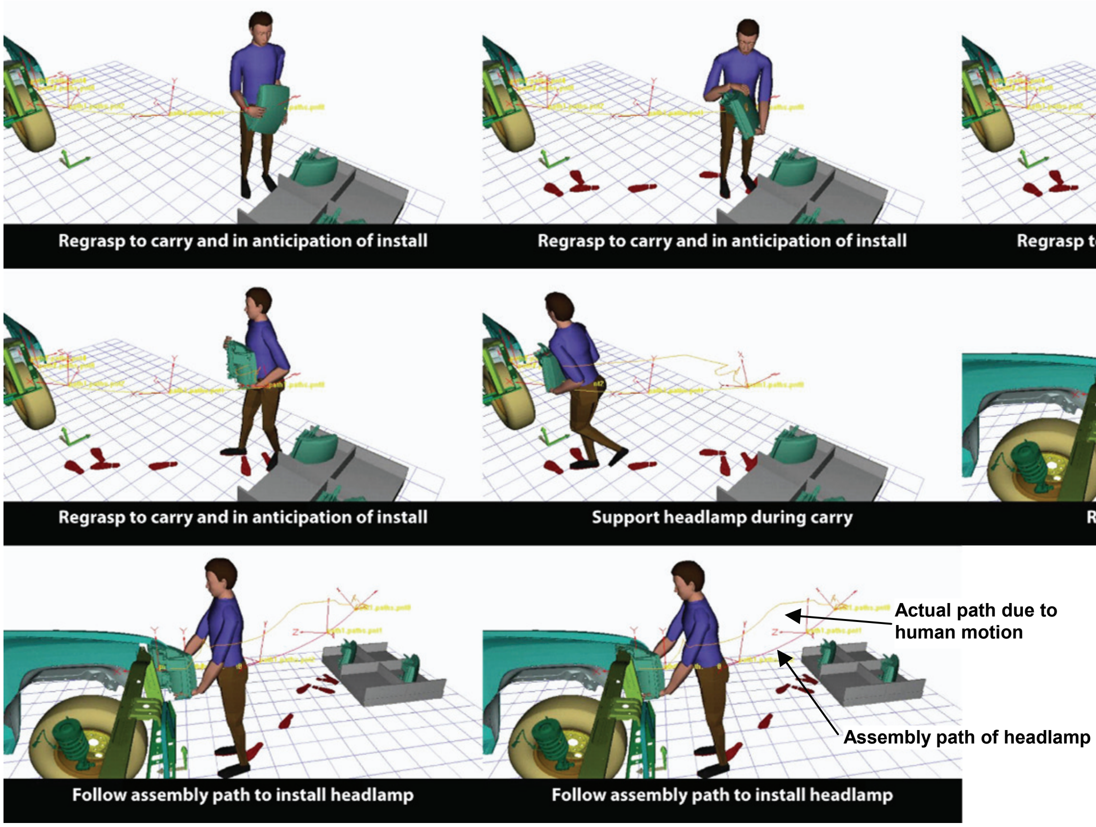


Figure 4. Screenshots captured from simulation results of "put headlamp".

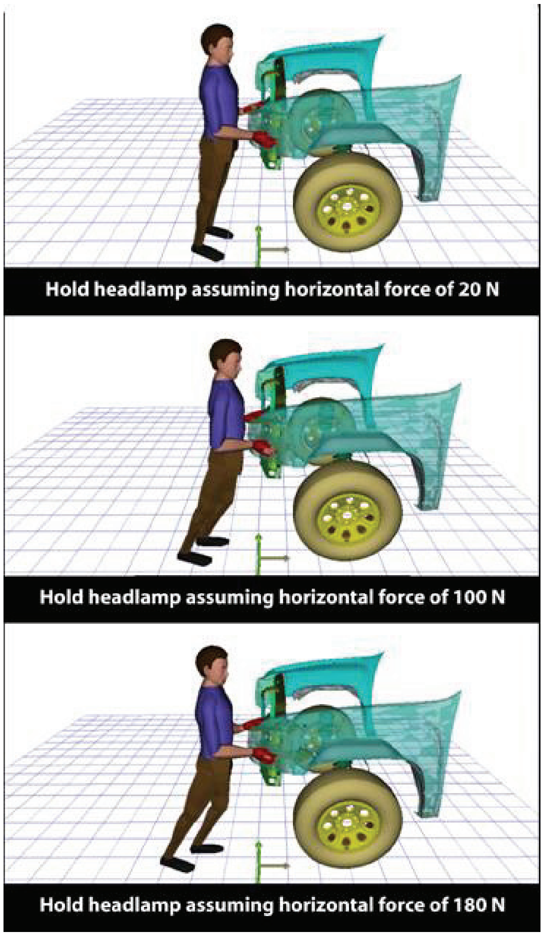
PUT HEADLAMP - The “put headlamp” work method involves positioning the headlamp onto the truck. The screenshots captured from a movie of the simulation generated for the “position / put headlamp” are presented in Figure 4. Note that since a headlamp can be bulky and/or of significant weight, the operator may need two hands to hold the headlamp. In this case, the operator needs to re-grasp the headlamp before transferring it to allow for better support during transfer. The operator may also re-grasp the headlamp in order to rotate it to the target assembly orientation for ease of assembly. During the installation, the hands / body of the worker should also not collide with the vehicle. The foot prints are automatically predicted by the TRANSIT stepping model in the HUMOSIM Framework to generate realistic whole-body stepping motions.

HOLD HEADLAMP - The “hold headlamp” work method involves holding the headlamp in position while the other worker secures the headlamp. The screenshots captured from a movie of the simulation generated for the “hold headlamp” are presented in Figure 5. The HUMOSIM Framework provides a built-in force-influenced posturing model that can estimate whole body posture while exerting forces (Hoffman et al., 2007). This model can predict force-exertion whole body postures that are validated by motion capture data. As shown in the Figure, the whole body posture changes while the magnitude of exerting force changes.

It should be noted that an object grasping model is required to predict two stable holding hand postures. These hand postures are sufficient for holding the part but may not be good for picking up the part. So, hand postures may be required for picking up the part in addition to hand postures required for holding the part in place. This indicates that object grasping is task dependent. In another words, a potential input to object grasping model is task specification.

SECURE HEADLAMP - The “secure headlamp” work method involves securing the headlamp to the truck while the other worker holds the headlamp. The screenshots captured from a movie of the simulation generated for the “secure headlamp” are presented in Figure 6.

Here the worker is using a right-angle tool to secure the headlamp. Note that the human hand can handle tools in numerous ways. The worker can use one hand to position the bolt and use the other hand to move the right angle tool. The two paths for the bolt and tool should not collide with each other. Hand clearance during movement should also be considered. Humans also rely on sensory feedback (vision or tactile) during tool use. All of these need to be addressed in a realistic collision-free tool-use model, which is currently not available in the HUMOSIM Framework.


Hold headlamp assuming horizontal force of 20 N

Hold headlamp assuming horizontal force of 100 N

Hold headlamp assuming horizontal force of 180 N

Figure 5. Screenshots captured from simulation results of “hold headlamp”. Three magnitudes of holding forces are shown.

DISCUSSION

SUMMARY OF MODELS AND KNOWLEDGE GAPS - By examining the steps, assumptions, and flow chart for all three case-study simulations, the models required in the simulation flow charts were identified and analyzed. These models and their associated inputs / outputs are summarized in Table 1. The availability of these models in the Framework is also listed in Table 1.

As shown in the Table 1, some of these models are available in the HUMOSIM Framework / motion algorithms. Some models are available but lack capabilities to simulate part handling motions as identified in the case studies. And some models are not available in the Framework (gaps). For the gaps, it is important to determine if they are available commercially, or reported by literature but not commercially available. Discussions of selected models and knowledge gaps are shown in this paper.

OBJECT GRASPING MODEL - As shown in Table 1, one important gap is an object grasping model that predicts realizable and stable grasping hand postures for an arbitrary part given a specific task and environment. The current HUMOSIM Framework does not provide the functionality for automatically predicting the location and shape of grasping hand posture given an arbitrary part and a specific task. It also does not provide the capability of determining whether a user-specified grasping hand posture has good quality (i.e. stable and able to balance external forces) for a given task. Based on work required to complete the three case-studies simulated, these functionalities do not exist in commercial digital human modeling software such as Siemens Jack 6.0.

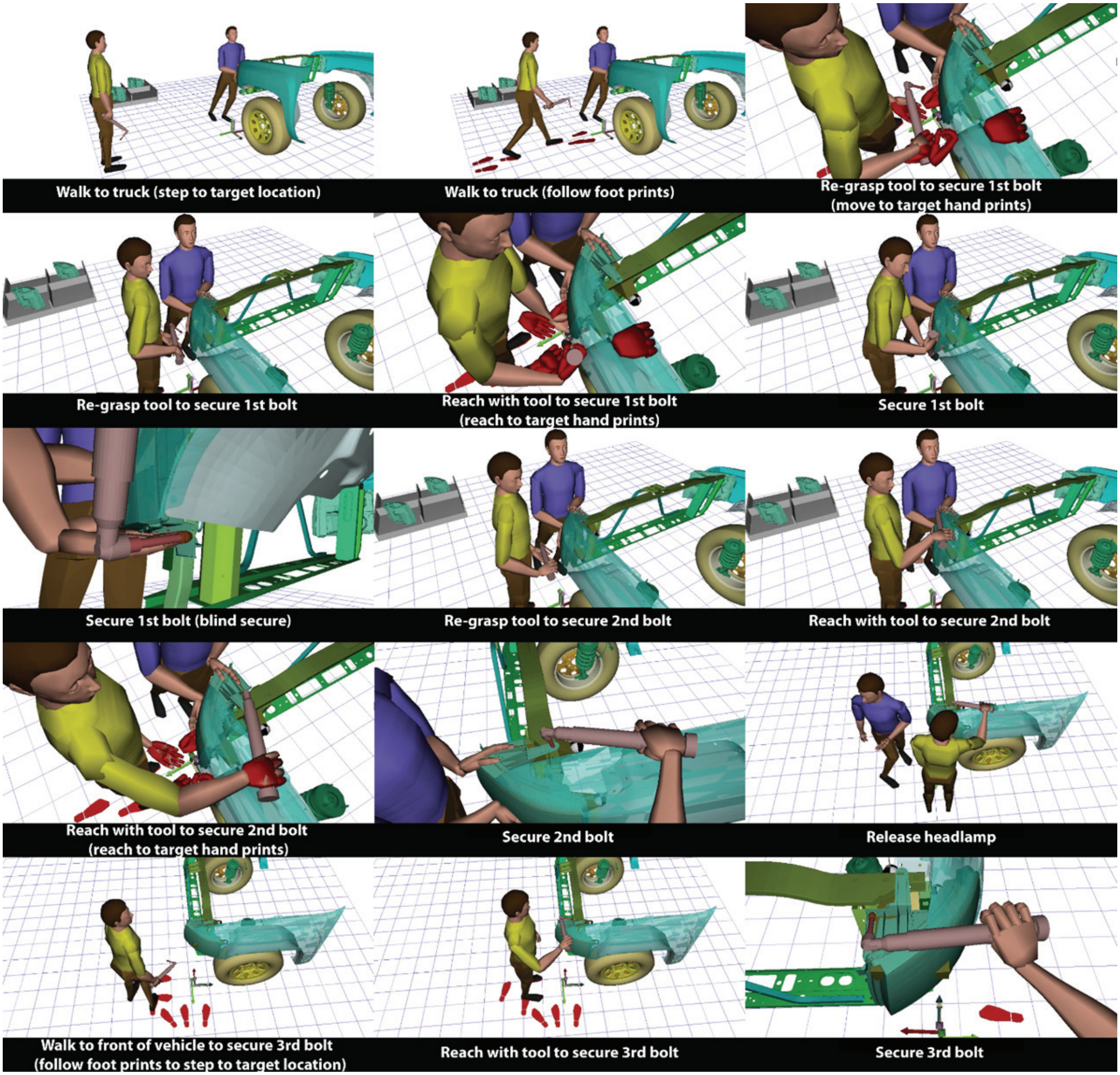


Figure 6. Screenshots captured from simulation results of “secure headlamp” showing three target configurations of bolts and right angle tool.

Table 1. Summary of models required for part handling simulation and knowledge gaps

No.	Model(s)	Input(s) (Key Parameters)	Output(s)	Availability (*)	Comments
1	Gaze model	• Part location	• Head movement	F	
2	Object grasping model: a model that predicts a realizable and stable grasping hand posture on an arbitrary 3D part	• Part geometry (CAD) • Part weight • Part material • Part center of mass • Part location & orientation • Environment geometries (obstruction such as the table on which the part is placed) • Task specification (pick up / push / insert part) • Required exertion force (F) • Worker location & orientation	• A realizable and stable grasping hand posture for a single hand • Or two hand grasping posture when both hands are needed	L(G)	Some object grasping models have been developed in the fields of ergonomics, robotics, and computer graphics. Human prehension movements are also studied in ergonomics and neuroscience. But the capabilities of current object grasping models are inadequate for digital human simulations.
3	Re-grasping model	• Part geometry (CAD) • Part weight • Part material • Part center of mass • Part location & orientation • Environment geometries (obstructions) • Task specification (support / carry / install part) • Worker location & orientation	Re-grasping motion (a series of release, reach, move, and position motions)	L(G)	Not available in the HUMOSIM Framework
4	A model that predicts foot locations according to hand locations	• Target hand locations • Environment geometries (obstructions)	Target foot locations	F(G), L(G)	Current Framework model predicts foot locations but does not consider obstacles.
5	Reach-ability checking model	• Target foot locations • Current worker location & orientation	Whether the target can be reached without walking	F(G), L(G)	Current kinematic models for reachability need to be augmented with biomechanics to take into account object characteristics. (available but lacking)
6	Stepping with/without carrying part model	• Worker location • Target foot locations • Environment geometries (obstructions) • Part geometry (CAD) • Part weight • Part center of mass	Collision-free walking / stepping motion	F(G), C(G)	The TRANSIT model (Reed and Wagner, 2007) is available to predict stepping. Additional functionality is needed to automatically avoid obstructions. The walk model in Task Simulation Builder can avoid obstructions but the avoidance behavior may not be physiologically reasonable.
7	Bracing (with/without part in hand) model	• Part geometry (CAD) • Part weight • Part center of mass • Target part location & orientation	• Whether bracing is needed • Bracing motion	F(G)	Model development is underway in the HUMOSIM Laboratory.

		• Required exertion force (F) • Environment geometries (bracing obstructions)	with/without part in hand		
8	Realistic reaching, moving, and positioning motion model	• Part geometry (CAD) • Part location & orientation • Environment geometries (obstruction such as the table on which the part is placed) • Task specification (pick up / push / insert part) • Required exertion force (F) • Worker location & orientation	Realistic motions for reaching, moving, and positioning objects or tools	F(G), L(G), C(G)	Hand motion prediction is available in the HUMOSIM Framework but the prediction is not necessarily collision-free. A variety of collision avoidance algorithms have been proposed (for a survey see Jimenez et al., 2001) but none are integrated into a general-purpose simulation structure such as the HUMOSIM Framework.
9	Force-influenced posturing model	• Current worker locations • Target hand postures • Required exertion force (F)	Whole body force-exertion posture	F	Available (Hoffman, 2008).
10	Grasping motion model	• Current worker hand locations • Target hand postures	Grasping motion	F(G), L(G)	A finger contact algorithm for human hands is available (Choi and Armstrong, 2006). Studies on the kinematics of grasping are underway in the HUMOSIM Laboratory.
11	Realistic model for tool-use motions	• Part geometry (CAD) • Part location & orientation • Environment geometries (obstructions) • Position / insertion path • Required exertion force (F) • Worker location & orientation • Tool using specification	Realistic tool using motion (1 or 2 hands)		Model is not available. Using tool at target location may require additional collision-free envelope requirements. The motions for using tool are different from the motions of positioning part.

* The models are listed with respect to their availability within in the HUMOSIM Framework, commercial software, and the literatures. The column code: (F) HUMOSIM Framework; (C) Commercial software; (L) Literatures. An added (G) indicates the capability is inadequate.

Object grasping models have been addressed to some extent in the areas of robotics and computer graphics. However, these models have limitations that warrant further work to address realistic digital human part handling simulations for ergonomic assessments. In these areas, object grasping models are often referred to as grasp synthesis or grasp planning models. Various approaches have been proposed to predict grasping, such as grasp quality optimization (Borst et al., 1999; Hester et al., 1999), dynamic simulation by decomposing object geometry into primitives (Miller et al., 2003; Goldfeder et al., 2007), and data-driven posture modification (Aydin and Nakajima, 1999; ElKoura and Singh, 2003; Li et al., 2007). These approaches focus on generating a grasping hand posture given the geometry of an arbitrary 3D object; but they usually do not take into account all relevant factors, such as object weight, center-of-mass location, and the required force. It should be noted that many of the current object grasping models are developed for robot manipulators. Human hands are generally kinematically and biomechanically different from robot manipulators (Valero-Cuevas et al., 2003; Miller et al., 2005). Some grasping models are developed for human hand for the purposes of computer graphics and animation. However, because of their purposes, these object grasping models usually do not consider human factors, such as hand anthropometry and hand strength. They are also not validated by real human grasping behavior. To develop an object grasping model for digital human simulations, it is necessary to understand the kinematics and biomechanics of the human hand and human prehension movements.

A number of published papers have addressed developing a realistic 3D kinematic or biomechanical human hand model for predicting grasping hand postures (Buchholz and Armstrong, 1992; Miyata et al., 2005; Pitarch et al., 2005; Choi and Armstrong, 2006; Yang et al., 2006; Endo et al., 2007; Endo et al., 2008). Various aspects of the properties of human hands are considered in these studies, such as hand anthropometry, skin stretch and bulge, finger joint movement patterns, and physiological joint constraints. Some factors such as skin deformation may increase the contact surface area and change the biomechanical equilibrium during grasping objects, thus affecting the grasp stability evaluation in an object grasping model. In addition, human hands have complex functional interactions among bones, ligaments, and muscles. These interactions may need to be addressed in a realistic object grasping model for human hands.

A challenge for current object grasping models is that they are not integrated with a whole-body model. As a result, the predicted grasping location and hand posture may look fine on an object, but may not be realizable for the prehension movement generated by the operator at a specific location and associated approach direction. Goussous (2007) attempted to integrate a data-driven object grasp model with a upper-body posture prediction model. However, the predicted whole body reaching and grasping postures are not validated by human motion data thus it is difficult to know if the predicted grasping location and hand posture is accurate or not. In addition, the current modeling approaches usually do not consider how grasps are affected by obstructions around the object. This limitation needs to be addressed in order to simulate some jobs such as grasping and manipulating hoses in an engine compartment.

Human prehension movements need to be studied to understand how human reaches and grasps objects. Prehension patterns that are unique to human hands are observed. A number of published papers suggested that humans tend to simplify prehension tasks by selecting one of only a few different prehensile postures appropriate for the object and for the task to be performed (for a review see Schieber and Santello, 2004). Some papers investigated the influence of object properties on prehension movements. For example, Paulignan et al. (1997) investigated the effects of location and size of cylindrical objects on prehension movements. They found that the degree of wrist flexion was little affected by the position of the object. Bae et al. (2008) investigated the temporal patterns of prehension movement in reaching and grasping tasks. Cylindrical objects of varying object sizes, distance to object, and orientation were used as targets. They found that the temporal parameters such as delay, open, close, reach, and total times, as well as aperture are affected by the distance to object significantly. These studies have provided valuable insights into the kinematics and mechanisms of prehension movements. The behavior models developed in these studies are based on observations and motion capture data from real human subjects; but these models are usually not very easy to generalize to a wide range of objects. As a result, the integration of these models into digital human motion algorithms is limited.

In summary, a good object grasping model should be not only able to generalize to a wide range of novel objects, but also be based on reaching and grasping behaviors of human subjects. The model also needs to consider the hand/arm approach motion in order to reflect realistic human behaviors and help determine a grasp location. The model predicted motions should be validated by human behaviors. We found that the current object grasping models lack the capabilities as described. Therefore, it is necessary to capture and identify the principal prehension patterns for a wide range of object shapes, locations, weights, etc. Using these data, a behavior-based object grasping model can be developed to predict grasping location and posture for a wide range of 3D parts for a given task. Other factors such as task specification and post-grasping behaviors may also need consideration in the model.

RE-GRASPING MODEL - As shown in Table 1, another important gap is a re-grasping model. Re-grasping motion can be defined as the motion to re-orientate an object to a target orientation. It can be accomplished by finger manipulations, or a sequence of reaching, grasping, moving, positioning, and releasing motions of the hands. According to the analyses from the automotive case studies, the purpose of re-grasping motion varies from gaining sufficient support of a part by re-grasping to carry a heavy part (i.e., headlamp) to re-orientating part/tool in order to perform assembly tasks. An automotive plant video survey showed that re-grasping is very common in assembly tasks, occurring in more than 90% of all observed tasks. Examples of re-grasping include operators using fingers on a single hand to rotate bolts and using two hands to rotate panels. Currently the HUMOSIM Framework does not provide the capability to simulate re-grasping motions. The commercial digital human modeling software such as Jack or Delmia also does not have the functionality to predict re-grasping motions.

Literature addressing re-grasping motions is limited, particularly literature that is grounded in systematic research. Elliott and Connolly (1984) proposed a taxonomy of manipulative hand movement. In this study, a number of digital coordination patterns were identified and classified. The classification is concerned with movements of the digits directed at manipulating an object within the hand. Hand postures have also been investigated in object manipulative tasks (Braido and Zhang, 2004; Todorov and Ghahramani, 2004) but none of the literature reviewed provided a quantitative model that predicts re-grasping motion. In the area of robotics, a number of re-grasp planning models have been proposed for the task of manipulating objects with the fingers of a single robot gripper (Rapela et al., 2002; Phoka and Sudsang, 2003; Sudsang and Phoka, 2003). These models compute a sequence of finger repositioning from one grasping configuration to another while maintaining a stable grasp but they do not address the two-hand coordinated re-grasping problem. They also usually do not take into account relevant factors, such as object weight and center-of-mass location. Erdmann (1998) proposed a model on two-palm manipulation for robots. The model considered the equilibrium between a friction cone and the line of gravity acting through the object's center-of-mass but the palms in this model are simplified and do not have fingers (no-prehension).

In summary, currently available models are insufficient for predicting re-grasping motion of human operators. Human re-grasping motion is different from a robot's grasping motion due to a difference in the kinematics of human hands/arms and robot grippers/arms. Additionally, there exists a challenge to predict two-handed re-grasping motion needs using an object grasping model which predicts the grasp locations of hands on work objects.

REALISTIC MOTION MODELS - Realistic reaching, moving, and positioning motion models are available in the HUMOSIM Framework but lack the capability of collision avoidance. The dynamic characteristics of reaching and object transfer motions have been investigated in the HUMOSIM Laboratory at the University of Michigan. Models for predicting reaching, moving, and positioning motions are implemented in the HUMOSIM Framework but these models are not yet integrated with collision avoidance. For part handling tasks in constrained spaces, such as reaching into an engine compartment, a collision-free motion model is critical to the accuracy and usability of the predicted postures / motions. Many methods have been developed for detecting and avoiding collisions (for a survey see Jimenez et al., 2001); the Jack 6.0 software also provides built-in collision detection functionality) but these methods are generally computationally intensive and require detailed scene markup and processing. In addition, most methods do not ensure that the resulting motion is realistic, although several have been made to address realism through motion modification (Dufour and Wang, 2005). A good obstacle avoidance algorithm will avoid penetrating obstacles using the same strategies humans use. For example, industrial workers often contact obstacles in their environments with their limbs when reaching into constrained areas (force-exertion posture with external bracing). Contact provides tactile feedback that may be useful for executing the motion, and may reduce the complexity of the movement planning.

There are some studies which tested generating collision-free realistic human motions in conjunction with the use of automatic assembly path planning tools and the current motion models. In the literature, there are several approaches to using a path planner to help when simulating human motions. Laumond et al. (2005) proposed two approaches from a robot motion planning point of view. The first approach consists of first planning a path for the part alone and then checking the feasibility of the solution by adding the mannequin. The user must specify the position of the hands on the part. The joint angles of the arms are then calculated by inverse kinematics. The second one considers the part grasped and the mannequin as a single system (DOFs of the body are added to the system). The authors concluded that the first approach performs quickly and the second approach is able to solve more constrained and difficult cases. While both approaches are capable of solving for a collision-free path for both the part and the mannequin in a very constrained space, they do not address the human body physiological constraints such as exertion forces. In addition, the grasping positions of the hands on the part are not automatically generated. Assembly tasks often require re-grasping to change the position of the hands on the part, which is not considered in this study. The approaches also do not consider whole-body motions such as squatting or bracing.

Yamane et al. (2004) developed an approach for animating characters by manipulating objects that combine the power of path planning with the domain knowledge inherent in data-driven, constraint-based inverse kinematics. A path planner was used to find a motion for the object such that the corresponding poses of the character satisfy geometric, kinematic, and posture constraints. The inverse kinematics computation of the character's pose resolve redundancy by biasing the solution toward natural-looking poses extracted from a database of captured motions. The computed path was then converted to a motion trajectory using a model of the velocity profile. They demonstrated that the algorithm is effective in generating animations across a wide range of scenarios that cover variations in the geometric, kinematic, and dynamic models of the character, the manipulated object, and obstacles in the scene. Simulating motion requires that similar part handling motions exist in the motion database. Due to the variety and complexity of part handling tasks, setting up a motion capture database to include a wide range of part handling tasks of ergonomic interest may not be economically feasible.

In this study, we evaluated the feasibility of generating collision-free realistic human motions by integrating assembly path planning with the HUMOSIM Framework. Using the headlamp installation case as an example, we tested a straight-forward approach which is to plan the assembly path of the headlamp first and then attach the mannequin to the headlamp. As a first step, a collision-free assembly path is generated for the headlamp to be installed in a truck as shown in Figure 4. The headlamp follows a collision-free path to be installed to the truck. As a second step, the hands of the mannequin are attached to the headlamp. The mannequin motions are generated using the track object functionality of the HUMOSIM Framework. The simulation results suggested that attaching the mannequin to the part as it is moved on a trajectory does not usually generate realistic worker motions. Awkward joints angles, unnatural postures / motions, and inaccurate balance during the transfer process are observed in the results. In fact, since the part is heavy, the operator may need to use two hands and may need to re-grasp it before installing it. Simply attaching the mannequin to the headlamp does not consider the required re-grasping motion. In addition, the assembly path predicted by path planner is usually a spline curve in 3D space. This path is usually different from the one generated by worker motions (note the difference between the assembly path and actual path of the headlamp in Figure 4).

In order to use the assembly path generated by a path planner as a reference when constructing a physiologically reasonable path, we can decompose the assembly path into three components / segments, such as target assembly configuration, insert / position path, and transfer path. Using the "put headlamp" task as an example (Figure 4), the target assembly configuration is the final location and orientation of the headlamp that must be accomplished by the worker. This can serve as an input to object grasping models. The insertion path denotes the path by which the headlamp is inserted into its final location on the truck. We can use the path planner to generate the path and then attach the mannequin to the headlamp. This approach is used in our simulations and the results are shown in Figure 4. The advantage is that collision-free positioning motion can be quickly generated in this case. However, a limit of this approach is that collision-free between the body and environment is not always guaranteed. In a very constrained space, such as an engine compartment, the hands may collide with many obstructions if simply attached to a moving part. In addition, if the truck is also moving (such as on an assembly line), the insertion path of headlamp may be unusable since it is generated off-line. An integrated collision-avoidance algorithm is needed for these cases.

CONCLUSION

This study identified 11 general models that are required to simulate part handling tasks, of which object grasping, re-grasping, and realistic tool-using models are not currently available. The HUMOSIM Framework has some capability to predict foot location prediction, assess reach-ability, generate stepping and walking, and create realistic simulations of moving, reaching, positioning objects, but improvements are needed. Gaze prediction, force-influenced posturing, and grasping motion models are already available in the HUMOSIM Framework and a bracing model is under development. The extensive research reported in the literature on grasp modeling and analysis suggests that progress is being made in that area, but commercial human modeling tools currently lack adequate object grasping and grasp/re-grasp simulation.

Assembly paths generated by part path planners are not directly useful for human modeling because the paths that a human would use will generally be different. Research is needed to allow a collision-free path generated by a path planning software to be used as one of several inputs to the human simulation. Ideally the collision-free path generation algorithm should be implemented within human motion generation models to satisfy both physiological constraints and the collision-free requirement.

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