HHS Public Access

Author manuscript

IISE Trans Occup Ergon Hum Factors. Author manuscript; available in PMC 2019 October 16.

Published in final edited form as:

IISE Trans Occup Ergon Hum Factors. 2018 ; 6(2): 64–75. doi:10.1080/24725838.2018.1491430.

Digital Human Modeling in the Occupational Safety and Health Process: An Application in Manufacturing

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Occupational Applications

Digital human modeling (DHM) and simulation software has been identified as an effective tool for evaluating work tasks and design alternatives without requiring the expense of physical mock-ups and production trials. Despite recent commercial advancements and a broader availability of DHM platforms, the peer-reviewed scientific literature lacks sufficient demonstration of the application of DHM software within an occupational safety and health process for mitigating exposures to physical risk factors in a real work environment. We describe the implementation of a commercially-available DHM platform as a component of an occupational safety and health process in a manufacturing environment over the course of one year. Success stories, challenges, and practical recommendations are discussed.

Keywords

modeling and simulation; musculoskeletal disorders; ergonomics tools and methods

1. Introduction

Occupational safety and health (OSH) practitioners are often responsible for evaluating workspaces to identify exposure to physical risk factors associated with musculoskeletal disorders (MSDs) (NIOSH 1997). While work design guidelines support the reduction of exposures to physical risk factors (Das & Sengupta, 1996; Mujumdar, Karandikar, & Sane, 2013; Wijk & Mathiassen, 2011), the persistent burden of MSDs among manufacturing workers suggests additional interventions remain necessary (BLS, 2015; NIOSH, 2008; NRCIOM, 2001). Proactive approaches to risk factor mitigation are of particular interest (Gatchel, Kishino, & Schultz, 2014; Robson et al., 2007).

Conflict of Interest

Co-author Victoria Roemig is an employee (senior application engineer) of SantosHuman Inc., the digital human modeling simulation and software company that is described in the manuscript. The authors are aware of no other potential conflict of interest.

Digital human modeling (DHM) and simulation software has been suggested as a valuable method for proactively understanding human performance limitations typical of a manufacturing environment (Chaffin, 2005; Kumar, Bora, Sanjog, & Karmakar, 2013). Many commercially available DHM platforms have been used to evaluate work tasks and design alternatives without requiring the expense of creating physical mock-ups (Fritzsche, 2010; Lämkull, Hanson, & Örtengren, 2009; Santos, Sarriegi, Serrano, & Torres, 2007; Sundin, Christmansson, & Larsson, 2004). Example platforms include Santos® Pro (VSR, 2004), Jack™ (Badler, Palmer, & Bindiganavale, 1999), RAMSIS (Bubb et al., 2006), and the AnyBody Modeling System™ (Damsgaard, Rasmussen, Christensen, Surma, & de Zee, 2006).

Despite the proliferation of DHM software platforms, examples in which DHM software was leveraged in the context of OSH practice are generally absent in the literature. In this paper, we describe how a commercially available DHM platform was incorporated within an existing manufacturing safety process. We provide examples of how the software was used to evaluate existing and new work tasks, examine design alternatives, and explore the effects of non-occupational risk factors on work task design criteria in the production environment. Success stories, challenges, and practical recommendations are discussed to provide greater context for practitioners who may be considering use of DHM software.

2. Methods

2.1. Overview of Facility and Safety Process

The activities reported here were conducted over one year in partnership with one manufacturing facility operated by a global producer of window and door assemblies for residential construction. During that year, the facility employed an average of about 400 hourly workers who logged a total of approximately 897,000 production hours.

The company had a well-established “safety program” designed by corporate-level risk management and operationalized under the oversight of the facility-level safety manager. The safety manager performed a daily facility walkthrough to identify deficiencies that could be immediately addressed. Ergonomics was also considered, and task evaluations were performed using the Washington State Ergonomics Checklist (Washington State Department of Labor and Industries, n.d.) to identify the presence of “Caution Zone” and/or “Hazard Zone” conditions. All “Hazard Zone” conditions were considered targets for corrective action.

The safety manager also chaired the facility’s safety committee, which met approximately monthly and included representation from facility management (e.g., the general manager, the production manager, and the human resources manager) as well as production team leads and workers. A standard meeting agenda included a review of progress toward safety-related elements of the facility’s strategic plan, updates on ongoing safety improvement projects, review/discussion of any injuries since the previous meeting, and discussion/prioritization of new safety improvement projects (including assignment of duties, as appropriate).

2.2. Digital Human Modeling and Simulation Software

The DHM and simulation software, Santos® Pro (SantosHuman Inc., Coralville, IA, USA), was made available to the safety committee. Primary motivations for providing the software were to help the safety committee more efficiently develop task configurations (both proactively and reactively), prioritize resource allocation, promote awareness of and educate employees on the topic of ergonomics, and avoid costs commonly associated with participatory ergonomics processes (van Eerd et al., 2010; Driessen et al., 2010). Santos® Pro is a commercially available software that embodies the research in predictive DHM and simulation that continues at the University of Iowa Virtual Soldier Research program, and it was selected due to the research team's familiarity with the software. Santos® predicts and analyzes human performance using validated mathematical models that consider strength, fatigue, range of motion, balance, vision, posture, external forces, clothing, equipment, and the environment as input parameters. Santos® Pro incorporates a full-body DHM (i.e., complete skeleton with associated degrees of freedom, including a high-fidelity hand model) with a realistic appearance. The software uses physics- and optimization-based posture prediction without the need for prerecorded motion data. Posture prediction algorithms also consider the relative movement of the eyes, head, and torso needed to peer around objects that would otherwise occlude a vision target. Additional tools include integration of common exposure assessment and task evaluation methods used in ergonomics practice, such as the NIOSH Lifting Equation (Waters, Putz-Anderson, Garg, & Fine, 1993) and Liberty Mutual material handling tables (Snook & Ciriello, 1991). Studies describing the development and validation of the SantosHuman DHM products may be found elsewhere (Abdel-Malek, Yang, et al., 2006; Frey-Law et al., 2010, 2012; Kim, Abdel-Malek, Yang, & Marler, 2006; Marler, Arora, Yang, Kim, & Abdel-Malek, 2009; Marler, Rahmatalla, Shanahan, & Abdel-Malek, 2005; Xiang, Arora, & Abdel-Malek, 2012; Yang, Kim, et al., 2007; Yang, Marler, Beck, Abdel-Malek, & Kim, 2006; Yang, Sinokrot, & Abdel-Malek, 2008).

2.3. DHM Introduction, Task Selection, and Simulation Process

The DHM software was introduced to facility management and the safety committee through a demonstration and discussion of how the technology had been applied in other industrial settings. The safety committee selected tasks to simulate at monthly meetings based on (i) known hazardous and/or physically demanding working conditions, and/or (ii) difficulty in evaluation using traditional exposure assessment methods (e.g., few observational exposure assessment tools have been shown to predict MSD risk for shoulder intensive tasks). Once a task was identified for evaluation, measurements needed to accurately simulate the work were obtained (e.g., physical workspace dimensions, weights and dimensions of parts, and applied forces, among others). Potentially relevant computer-aided design files of the facility and/or equipment were not provided for the development of DHM scenarios. This limitation was overcome by working with the safety manager and the production employee most familiar with the work to obtain relevant images and videos of the workstation or work task being completed following facility recommended best practices. These pieces of information were then used to create scenarios in the DHM environment, perform static analyses at important, representative moments of each task (e.g., peak forces, extreme postures, etc.), and results and recommendations were presented to the

safety committee at a monthly meeting. Metrics used to evaluate tasks and workstation designs included, but were not limited to, joint displacement (defined as "the difference between current joint angles and angles that constitute a predetermined neutral position" [Marler, Arora, Yang, Kim, & Abdel-Malek, 2009, pg. 927]), joint torque, static fatigue (i.e., predicted time to joint-specific fatigue as a function of joint torque and joint displacement), L5/S1 compression and shear forces, and predicted discomfort. These metrics are generally available across DHM platforms (Chaffin, 2008), although the underlying software architecture and algorithms differ. The safety committee used the information to propose modifications, depending on the purpose of the simulation.

3. Results

Seven distinct work tasks were simulated during the year, with numerous extensions and sub-analyses performed. Simulation objectives could be broadly categorized as: 1) to characterize exposure to physical risk factors associated with MSDs; 2) to develop and/or evaluate alternative workstation designs intended to reduce exposure to physical risk factors; and 3) to evaluate the role of non-occupational factors on exposure to physical risk factors during the completion of a work task. Annotated details of the work tasks are included in Table 1 with examples described in the following subsections

3.1. Evaluations of Existing Work Tasks

Based on prior low back injury reports, the safety committee was interested in performing an analysis to determine the maximum load their manual material handling (MMH) carts should hold (Table 1, Task 1; Figure 1). MMH carts used in the facility were typically designed to carry approximately 50 panes of window glass with an average mass of 18 kg. Most of the carts were fully loaded when moved and approached a maximum possible weight of 1134 kg, considering both the weight of the cart and the load. To the authors' knowledge, this DHM analysis was the first analysis performed to assess the risk associated with moving the carts.

To perform this DHM assessment, a standard cart's dimensions were measured and estimates of forces required to move the carts were obtained (both empty and fully loaded and in both pushing and pulling configurations) using an electronic dynamometer (Baseline®, Nexgen Ergonomics, Inc., Pointe Claire, Quebec, CAN). To estimate the maximum load a cart should hold, DHM outputs of lumbosacral (L5/S1) compression and shear forces at the initiation of pushes and pulls were generated across a variety of pushing/pulling postures and cart weights based on biomechanical performance models (Potvin, Norman, & McGill, 1991, 1996; Potvin, Norman, & McGill, 1991). Specifically, forces were applied to the Santos® Pro avatar at the wrists and pointed away or towards the body, as relevant, using the "point load tool". Predicted L5/S1 shear and compression forces were compared to recommended limits of 3400 N for compression and 500 N for shear (Gallagher & Marras, 2012; Waters, Putz-Anderson, Garg, & Fine, 1993).

The results suggested a maximum load of approximately 227 kg, or 12 panes of window glass, to maintain L5/S1 compression and shear within acceptable limits. Additionally, the results identified pushing, particularly straight ahead, as the preferred mode to move the

carts. The safety committee used this information to update its training procedures and facility-wide cart loading recommendations.

3.2. Development and Evaluation of Alternative and New Workstation Designs

A common fastening task (Table 1, Task 6) was reconfigured using recommendations based on DHM analyses. The safety committee selected this task for analysis because an employee reported pain in the dominant shoulder and distal upper extremity. Results of a preliminary hazard assessment suggested a mismatch between the orientation of the tool and the orientation of the work piece, leading to potentially high upper extremity forces in a non-neutral posture (Figure 2A). General ergonomics principles would suggest replacing the pistol grip driver with an in-line tool; however, this was not feasible due to restrictions in routing the air line and an alternative solution was required.

Information collected to simulate the task included worktable dimensions, the weight of the driver, and video recordings of the task being completed. Measurements of the force required to operate the tool in different orientations were obtained using a force transducer and production materials. This information was then used to simulate the original task (Figure 2A) and several alternative designs that allowed the tool to be oriented at various angles. Metrics used to evaluate these options included shoulder joint displacement, shoulder joint torque, and estimates of the percentage of the population capable of performing the task (based on maximum joint torque distributions embedded within the DHM software). Results suggested that the workstation should be redesigned to include (i) an adjustable fixture to allow the work piece to be oriented at angles from the horizontal between 30° and 60° (Figure 2B) and (ii) height adjustability to best accommodate workers of different stature.

In another example, several workstation design options were evaluated prior to full installation of a new painting line (Table 1, Task 7). Potential designs were brainstormed and discussed by the safety committee and manufacturing engineering, such as working with the window frames lying flat on a table (Figure 3A and 3B) and in different upright orientations (e.g., Figure 3C and 3D). Similar to the DHM simulations described earlier, metrics such as joint displacement, static fatigue, L5/S1 compression and shear, and predicted discomfort were examined. Outputs were also generated using the Santos® “Zone Differentiation” plug-in, which analyzes the space surrounding the body based on the ability to complete simulated task requirements (Figure 4). In addition to reach envelopes, Zone Differentiation considers competing objectives, such as ability to see, object avoidance, and reaction to external forces. Ultimately, information from the simulations was used to select the design that reduced predicted biomechanical loads to the greatest extent while minimizing predicted discomfort (Table 2; Figure 5).

3.3. Considering Non-occupational Risk Factors

Most exposure assessment methods used by OSH practitioners do not consider non-occupational risk factors, such as personal characteristics that vary considerably between individuals (e.g., body mass index [BMI]). To illustrate the potential effects of personal risk factors such as an unhealthy BMI (i.e., overweight or obese classification) on employee

safety and health, the safety committee requested that the MMH cart moving task (Table 1, Task 1) be expanded to include males and females with different BMI classifications.

To address this request, male and female avatars with a normal BMI (≥18.5 kg/m2 and ≤24.9 kg/m2), an overweight BMI (≥25.0 kg/m2), and an obese BMI (≥30.0 kg/m2) were implemented into the MMH cart task previously described in Section 3.1 (Table 3; Figure 6). Strength estimates for a 5th, 50th, and 95th percentile human based on previous research (see Marler et al., 2012; Frey-Law et al., 2012 for more information and example experimental procedures) were considered for each BMI and gender combination. "Strength" is mathematically represented in Santos® Pro as a function of joint angle based on net muscle torque produced about the joint considering contraction velocity, muscle length tension relationships, and muscle moment arms (Marler et al., 2012). Because the simulation engine predicts postures, differences in the avatar dimensions as described in Table 3 resulted in differences in estimated joint torques and other summary measures of interest.

In general, results indicated that while each avatar could complete the task, relative biomechanical demands increased as BMI increased and strength profiles decreased. Specifically, motion restrictions and reduced capacity to generate joint torque resulting from increased BMI and decreased strength led to increased demands. The safety committee used this information to increase employee engagement with facility-wide workplace wellness activities occurring at the time, such as a walking program, strengthening exercises, and health coaching activities.

4. Discussion

In general, the DHM simulation software was found to be an effective tool for augmenting traditional approaches to the identification of physical risk factors for MSDs in a manufacturing environment. The technology was considered especially useful for simulating work scenarios that may be difficult to assess using traditional exposure assessment methods. For example, few observational exposure assessment tools have been shown to predict MSD risk, particularly for shoulder-intensive work tasks such as the fastening task (Table 1, Task 6), and/or sufficiently simulate personal characteristics such as BMI. The DHM software employed in this application allowed for realistic representations of several body types, postures, and environmental constraints that made it easier to envision and efficiently analyze the work as well as educate safety committee members to recognize aspects of work tasks that increased exposure to physical risk factors. We described several situations where the DHM software provided information that improved operational decision-making. Importantly, the safety committee appeared to become more comfortable with the technology as time progressed, and they sought opportunities to proactively design work processes to reduce potential OSH risks (e.g., the paint line task; Table 1, Task 7) rather than reacting to incidents and reports of pain or other symptoms.

Despite the positive outcomes resulting from completion of the various DHM projects, several challenges were identified throughout the project year that limited the potential impact of the effort. One challenge was determining who would be responsible for

developing the simulations. Originally, the project was organized with the intent of providing the Santos® Pro software and necessary training to two engineers at the manufacturing facility who would have the ability to develop simulations independently. This did not occur, however, as both engineers changed jobs shortly following completion of the training process. Instead, the project research staff acted as a conduit between the safety committee and a professional engineer working for the DHM software company. The primary advantage of this situation was that the professional engineer could develop simulations at a faster pace than the relatively inexperienced manufacturing engineers. The primary disadvantage was that more time was required to gather the information necessary to develop the simulations and communicate those details to the professional engineer. For example, because relevant computer-aided design files of the facility and/or equipment were not immediately available, valuable safety manager and production employee time was used to obtain images and videos of the workstation or work task being completed following facility recommended best practices. Because of this limitation, it is unlikely that the DHM software will continue to be used by the manufacturing facility upon completion of the project as no member of the safety committee has the necessary expertise. Moreover, the example underscores a potentially common scenario that has a high likelihood of occurring in many typical manufacturing environments where turnover may be common. The lack of personnel trained in the application of DHM simulation appears to be a primary limitation for the adoption of the technology on a broader basis.

While facility leadership remained relatively unchanged during the course of this project, a change in corporate leadership did lead to the institution of several new corporate initiatives. These initiatives often took precedence over those at the facility level, including many activities recommended by the safety committee. The direct impact of these corporate changes on the DHM project is unknown. However, it is reasonable to expect that had the corporate changes not occurred, the safety committee may have had more opportunities (and resources) to examine, conduct, and implement DHM-related projects and modifications.

The safety committee indicated that cost was a potential barrier to implementing several of the suggestions resulting from the DHM analyses. For example, in one example not previously discussed, the DHM was applied to a task that involved pushing/pulling a large glass frame along the ground to the next workstation. Although the DHM was useful for determining risk factors associated with the task, and for considering potential solutions (e.g., implementing roller tracks in the ground rather than above the ground), resources were not available to implement potential solutions at the time. Along these lines, although DHM software has been identified as an effective tool for evaluating work tasks and design alternatives without incurring the expense of physical mock-ups and production trials, use of DHM software is not without cost. Training and simulation development time in addition to the expense of the software itself are just some of the costs associated with using DHM software. Unfortunately, specific information on the incidents associated with the presented work tasks were not available, limiting our ability to characterize the extent of the problems as well as the potential return on investment of this particular DHM effort.

Finally, while DHM platforms have advanced substantially in recent years, the software still lacks an ability to efficiently simulate “the human variability component” inherent to human

movement and work (Perez & Neumann, 2015). Many times, requests from the safety committee could not be simulated because of limitations of the underlying capabilities of the computationally intensive, mathematical predictions. Example tasks that were more difficult to simulate because of this variability included jobs involving complex motions and/or manipulations (e.g., hand intensive tasks). Additionally, while personal characteristics such as BMI and gender were simulated, the avatars used to do so were developed to represent an "average" or "typical" person with different strength profiles. This made it difficult to address questions about how unique characteristics (e.g., various body shapes, segment lengths) may affect results. Key characteristics of real human motions, such as smooth velocity and acceleration, were generally ignored (Zhang & Chaffin, 2005). Further development of more realistic DHMs is necessary, as is additional research to understand the relationship between strength and BMI (e.g., Massy-Westropp et al., 2011), particularly as it pertains to DHM applications.

In our experience, integration of a DHM platform into an OHS process depended greatly on the availability of a professional engineer trained in the application of the DHM software and trained ergonomists to work with the safety committee and demonstrate the value of DHM as an operational decision-making tool. With this guidance, the safety committee appeared to gain a greater appreciation for the augmented approach the application of DHM software offered to the identification and control of physical risk factors for MSDs that previously relied on simple checklists. Limited resources, employee turnover, and challenges developing complex models served as barriers to a more deep-rooted integration. Investigators and practitioners considering integrating a DHM platform into an OSH process in a manufacturing environment should identify methods to ensure that the advantages and disadvantages of a DHM approach are understood and that safety committee personnel become adept at using the software to promote its use.

The following conclusions may be drawn from this application:

Strengths and value associated with integrating the DHM software into the OHS process:

Ability to evaluate design alternatives proactively without need for prototypes

- Ability to proactively evaluate design configuration on different sized individuals
- Improved communication and awareness of ergonomic issues among stakeholders
- Identification of potential hidden costs, such as elevated risk of injury with obesity

Primary challenges associated with integrating the DHM software into the OHS process:

- Developing expertise with the DHM software and time challenges developing analyses
- Availability of facility and product data for use in the simulations
- Limited resources and employee turnover

Acknowledgments

Funding

This research was supported by the Healthier Workforce Center of the Midwest (HWC) at the 73 Digital Human Modeling in Manufacturing University of Iowa and the Deep South Center (DSC) for Occupational Health and Safety Education Research Center. The HWC and DSC are supported by Cooperative Agreements No. U19OH008868 and No. 2 T42 OH008436–13 from the Centers for Disease Control and Prevention (CDC)/National Institute for Occupational Safety and Health (NIOSH). The contents are solely the responsibility of the author(s) and do not necessarily represent the official views of the CDC, NIOSH, HWC, or the DSC.

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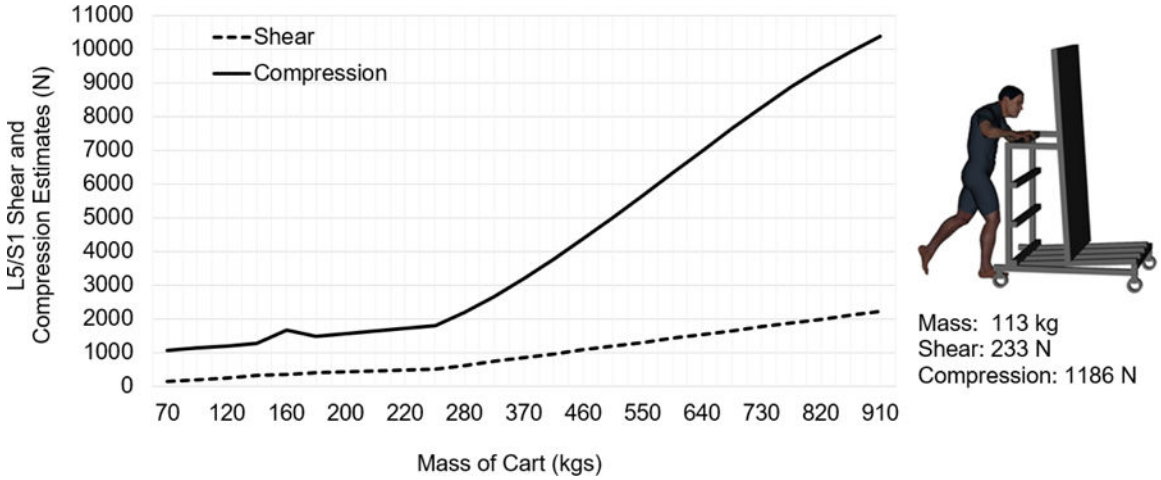

Figure 1.

L5/S1 shear and compression estimates for Avatar Santos® while pushing a manual material handling cart.

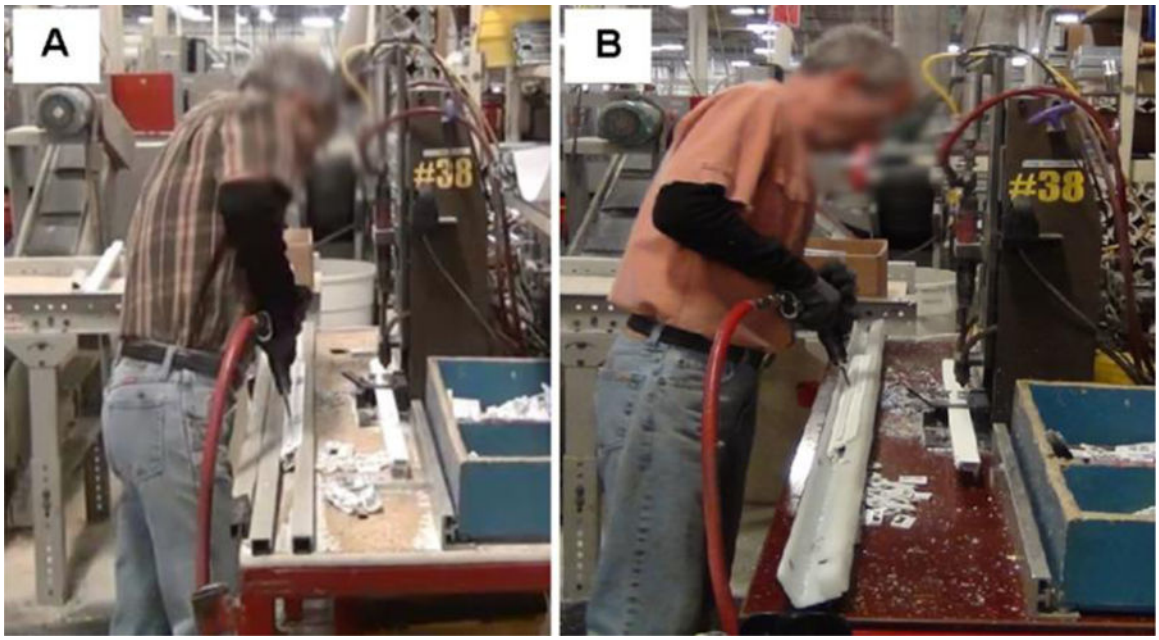

Figure 2.
Worker performing fastening task on: A) original workstation, B) adjustable workstation.

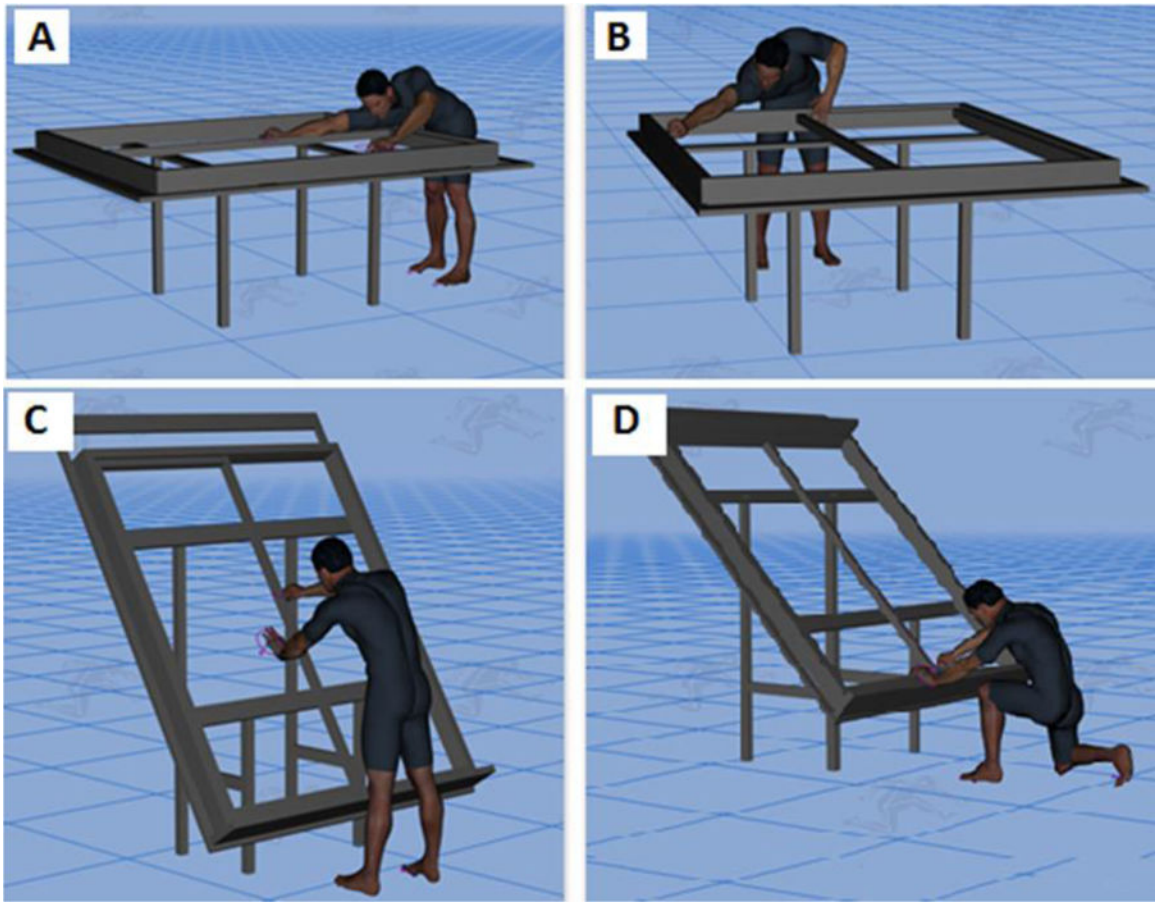

Figure 3.
Simulations showing the avatar Santos® working with a window frame lying flat from the (A) long end and (B) short end of the window, as well as working with a window frame in a canted orientation while (C) standing and (D) kneeling.

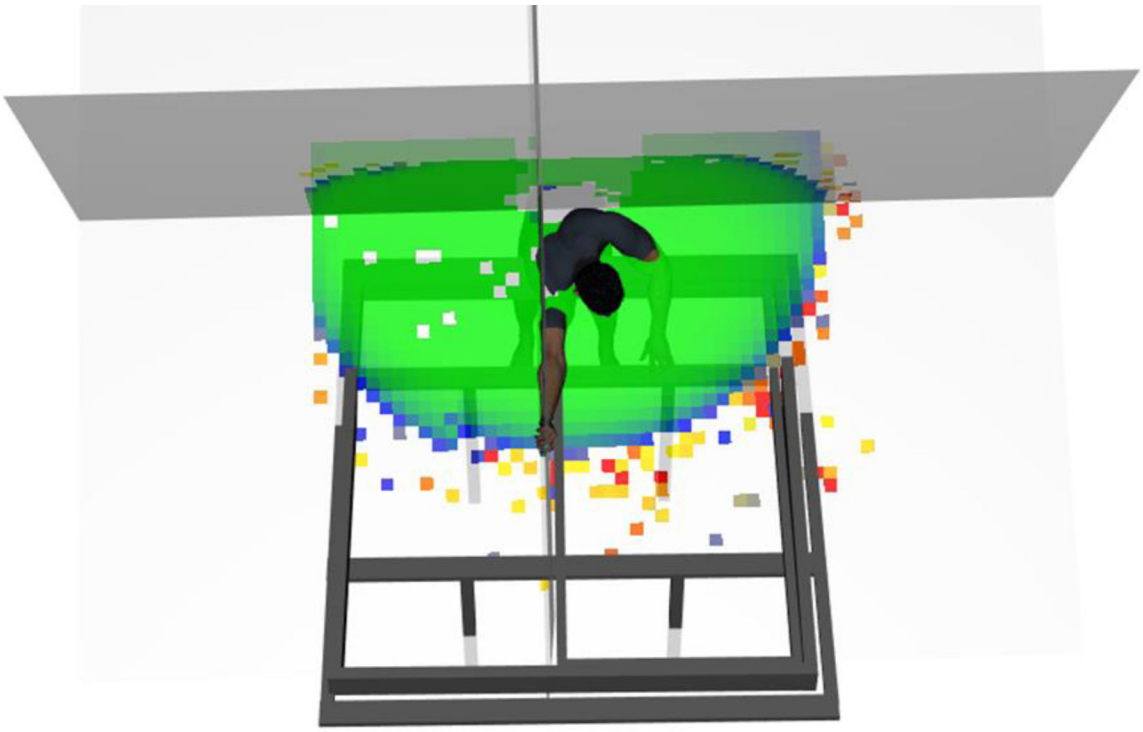

Figure 4.
Santos® Pro Zone Differentiation plug-in displaying range of motion for the paint line work task completion.

Figure 5.
Adoption of the canted window orientation for the paint line allowing both standing and kneeling postures that reduce reaching.

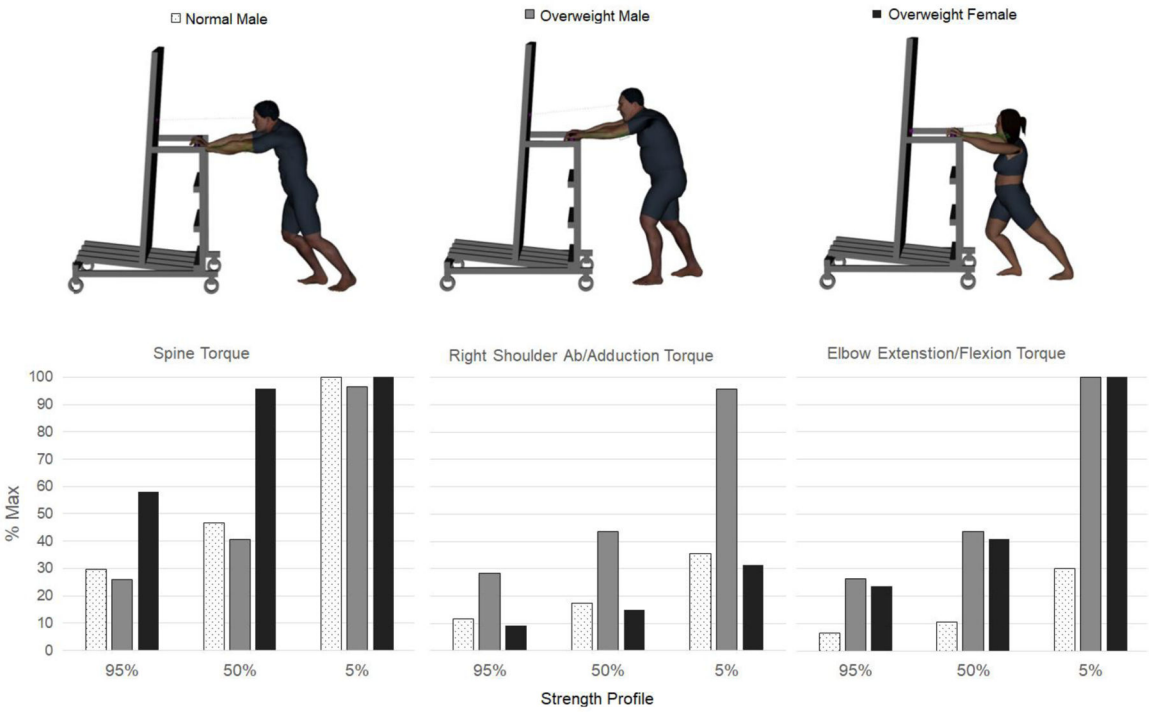

Figure 6.
Various avatars moving manual material handling carts and example results.

Table 1.

Description of work tasks simulated using Santos® Pro.

	Work Task	Task Deficiency / Concern and Simulation Objective	Primary DHM Capabilities Applied	DHM Simulation Outcome and Resulting Intervention(s)
1.	Manual Material Handling using Transfer Carts	**Concern:** Overloaded carts may increase risk for MSDs, particularly of the low back. **Objective:** Identify and characterize physical risk factors and determine maximum loaded cart weight.	● Joint torque ● Static fatigue ● L5/S1 compression and shear ● Alternative avatars with various strength profiles	● Identified and proposed cart weight limit of approximately 227 kg. (500 lbs.). ● Modified cart standard operating procedures. ● Promoted training to reduce pulling / pushing from side of carts. ● Increased cart wheel circumference and installed foot brakes on new carts. ● Educated safety committee members on the potential effects of personal risk factors such as an unhealthy BMI on task performance.
2.	Constructing Window Sashes	**Concern:** Employee reports of distal upper extremity pain. **Objective:** Identify and characterize physical risk factors.	● Joint displacement ● Joint torque ● Static fatigue	● Identified most strenuous postures. ● Promoted training of two-hand manual material handling and use of power grips (e.g., in-line tools).
3.	Final Window Construction	**Concern:** Work task involves heavy lifting. **Objective:** Identify and characterize physical risk factors associated with task.	● Joint displacement ● Joint torque ● Static fatigue ● Predicted discomfort ● NIOSH Lift Analysis	● Redesigned workstation to move pallets and carts closer to production line to reduce manual material handling. ● Promoted training of two-handed manual material handling and limiting twisting. ● Educated safety committee members on NIOSH lift analysis tool.
4.	Wrapping Products for Transport	**Concern:** Two conveyor options were in use. **Objective:** Identify and characterize physical risk factors associated with the task and select conveyor height.	● Joint displacement ● Static fatigue ● L5/S1 compression and shear ● Discomfort	● Identified carrying products as the riskiest subtask. ● Suggested adjusting conveyors to a position between conveyor heights originally used in the facility. ● Promoted training of two hand lifts.
5.	Constructing Patio Doors	**Concern:** Work task involves heavy lifting. **Objective:** Identify and characterize physical risk factors associated with task.	● Joint torque ● Static fatigue ● L5/S1 compression and shear	● Compared two work task designs. Both had advantages and disadvantages. ● Promoted training of two person manual material handling for some subtasks (e.g. glass handling) and improved signage.
6.	Pneumatic Fastening Task	**Concern:** Employee reports of shoulder and distal upper extremity pain. **Objective:** Identify alternative workstation design.	● Joint displacement ● Joint torque ● Stability	● Redesigned workstation to allow adjustable drilling angle and work height.
7.	Product Painting and Cleaning	**Concern:** New line to be implemented. **Objective:** Identify and characterize physical risk factors and proactively evaluate workstation design options prior to full implementation.	● Joint displacement ● Static fatigue ● Discomfort ● L5/S1 compression and shear ● Zone differentiation	● Selected workstation carts that allowed workers to remove paint tape in the center of windows without leaning across the table (especially for larger windows or doors). ● Informed training practices to promote health and safety.

Table 2.

Simulation outputs for the L5/S1 joint of the Santos® Pro normal avatar for assessing paint line workstation design options.

Orientation	Joint Displacement[a] (unitless)	Static Fatigue[b] (seconds)	L5/S1 Compression (Newtons)	Predicted Discomfort[a] (unitless)
Flat - Long	69	320	1763	76
Flat - Short	68	192	2616	73
Canted - Stand	44	630	1580	67
Canted - Kneel	40	594	1600	79

[a]Smaller value is better.

[b]Static fatigue is the predicted time to fatigue of a body joint assuming a static posture (Smaller values suggest faster fatigue onset).

Table 3.

Avatar dimensions used to simulate the effect of non-occupational factors on work task design criteria

Avatar	Height (cm)	Body Mass (kg)	Body Mass Index (kg / m^2)
Normal-weight male	182.6	63.7	19.1
Overweight male	182.6	79.7	25.9
Obese male	178.4	95.7	30.1
Normal-weight female	161.4	46.3	17.8
Overweight female	161.4	58.7	24.0
Obese female	158.8	71.1	28.2