SmartManikin: Virtual Humans with Agency for Design Tools

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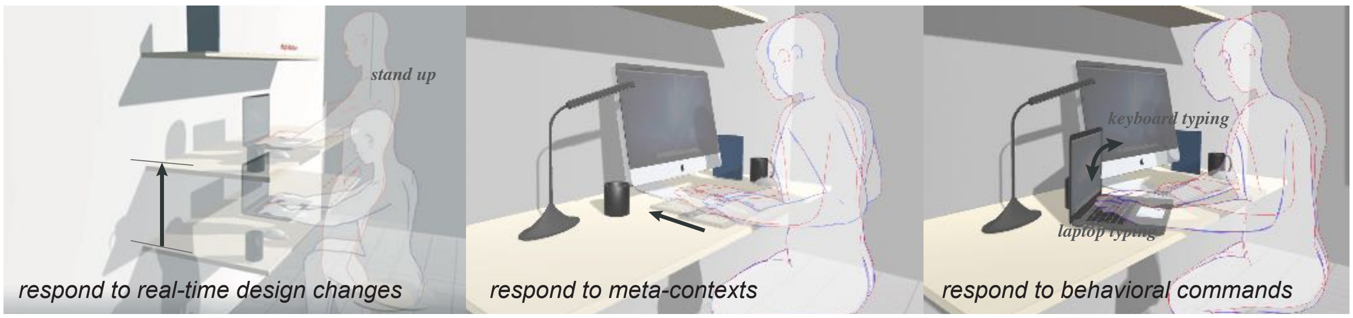

Figure 1: SmartManikin is a virtual mannequin with agency that simulates natural poses in digital design tools. It responds to real-time design changes (left) and behavioral action commands (right). It also responds to meta-level contexts, such as objects that are related to the design (center).

ABSTRACT

When designing comfort and usability in products, designers need to evaluate aspects ranging from anthropometrics to use scenarios. Therefore, virtual and poseable mannequins are employed as a reference in early-stage tools and for evaluation in the later stages. However, tools to intuitively interact with virtual humans are lacking. In this paper, we introduce *SmartManikin*, a mannequin with agency that responds to high-level commands and to real-time design changes. We first captured human poses with respect to desk configurations, identified key features of the pose and trained regression functions to estimate the optimal features at a given desk setup. The SmartManikin's pose is generated by the predicted features as well as by using forward and inverse kinematics. We present our design, implementation, and an evaluation with expert designers. The results revealed that SmartManikin enhances the design experience by providing feedback concerning comfort and health in real time.

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CCS CONCEPTS

• **Human-centered computing** → *User interface programming*; • **Computing methodologies** → *Interactive simulation*;

KEYWORDS

virtual human, human agent, design tool, simulation

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1 INTRODUCTION

When designing for people, industrial designers need to carefully consider the human body including ergonomics, safety, and comfort [35]. Therefore, the human body has been used as a design medium; for example, methods such as "bodystorming" [6, 44, 52] or "experience prototyping" [5] are dominantly used to understand human needs, while "usability tests" are conducted with potential users in the latter stages.

In a similar manner, several *digital design tools* employed virtual human bodies to fit the product to desired use scenarios. Some systems let people design on their body [14, 15, 49] or virtual mannequins [60], and use their bodies as canvases. Other tools use bodies as input [38, 64] and translate embodied explorations directly into their designs. A few systems provide physical or ergonomic simulations with virtual mannequins [1, 50, 55]; however it is still hard for designers to interact with virtual mannequins intuitively, especially when people are in the middle of the complex design process.

Badler [42], the pioneer of using virtual humans in design tools, explained this with three paradigms for posing virtual humans: 1) *direct* manual manipulation with kinematics, 2) *showing* it what to do [19, 25, 43, 61, 64], and 3) *telling* it what to do. Whereas most of the existing tools employ the first and the second paradigm, we explore the use of the third paradigm, a mannequin with agency that automatically responds to design contexts and high-level commands.

We introduce *SmartManikin*, a virtual human with agency for design tools. The agency judges and generates the most natural poses based on a) high-level action commands, such as *"type"*, or *"reach a shelf"*, and b) real-time design changes. For example, if a designer lowers a surface in the CAD model, the mannequin bends to show the reachability. Also, if the designer raises a shelf too much, the mannequin indicates that it is not able to use it.

Whereas most design tools support ergonomic evaluations for health and safety, our formative study revealed the importance of conveying knowledge regarding comfort. Therefore, we systematically 3D-captured comfortable human poses, identified key features, and trained the regression functions of these features to predict the proper features at a given desk setup. In this way, when a user makes a design change, the SmartManikin's agency can update the predicted features with forward and inverse kinematics in real time.

There are several limitations to this work. We trained our system with 3D skeleton data captured by short-term observations; therefore the influence of body physique or anthropometrics on pose generations and long-term comfort were not taken into account. Also, we only applied SmartManikin in a desk configuration tool; we chose a desk as it is frequently personalized furniture with a variety of purposes and complex considerations [4]. Still, our prototype was solid enough to propose our novel concept and to evaluate it with professional industrial designers.

This paper makes four contributions: 1) Design strategies for virtual human agency in design tools derived from a formative study, 2) Generating comfortable and natural poses using 3D-captured data, 3) SmartManikin, a virtual mannequin with agency that updates poses according to real-time design changes or commands, and 4) Initial feedback from expert designers and discussions for future work.

2 RELATED WORK

Virtual humans have been applied in various fields such as ergonomics and usability in multiple industries ranging from furniture and automotive to production simulations and games [40]. Our research bridges the existing work on virtual human agents and digital design tools.

Virtual Humans as Digital Design Tools

Jack [42] is an early example of a virtual human that evaluates ergonomics. It supports anthropometric scaling and joint-limit information for a given target population and includes a library of pre-programmed 28 postures. However the relationship between the pose and the CAD model is left to the designer.

Several systems in HCI employ a virtual human as a design constraint or reference. Mirror Mirror [49], ExoSkin [15], and Tactum [14] let people draw on their bodies while DressUp [60] provides virtual mannequins as a canvas. Some researchers used postures as references to design a bicycle [20, 24], furniture [39], or various hand-held products [33]. However, these systems only support static poses.

Beyond static poses, Kim et al. [31] populates architectural spaces with digital humans to simulate scenarios [6, 7] in service design. We build upon this work to make a virtual human simulate a sequence of actions (e.g., a transition between watching a video and reading a book) to support designing for real-life use with agency.

Posing Virtual Humans

Inverse kinematics or forward kinematics are the commonly applied methods to pose virtual humans [3, 22, 47]. Several improvements are suggested, such as making virtual humans imitate the poses of simple line-drawings [2, 21], tangible modules [19, 25, 43, 61], or embodied gestures [9, 33, 38, 64].

Instead of direct manipulation or imitation, a few systems showed virtual humans with agency that respond to high-level commands [42]. Johnson et al. [26] proposed the concept of *"intentional control"* that allow users to control a virtual character at the *behavioral* level rather than at the *motor* level. Whereas they applied this concept in conjunction with tangible puppets, we build upon this work in a digital space to simulate multiple use-actions with high-level commands.

Autonomous virtual humans as non-player characters have been actively researched in the game industry for decades. They *perceive* the virtual environment [37, 46], and *make decisions* to choose appropriate actions for a given context [17, 18, 30, 59] with respect to age [12], personality [16], motor skills [54], and emotions [56]. We build upon this concept of context-aware motions and make SmartManikin respond to real-time design changes.

Context-Responsive Motions

DreamSketch [29] is a sketch-based interface with a constraint-based solver to interactively generate geometry that satisfies predetermined constraints. The prototype includes a posable mannequin whose joints can be constrained to sketch entities dynamically. We build upon this work, but instead of designers specifying constraints, we aim to make the virtual mannequin context-responsive in relation to other objects.

In computer graphics, researchers have been developing techniques to automatically generate human poses appropriate for a given environment. A widely studied approach is to adapt existing motion data for a particular environment to a different environment, such as furniture configuration [23, 27, 34, 57, 58, 65]. Another line of work attempted to find appropriate poses for a given object, such as placing one's hands on bicycle handlebars [32], by using machine learning methods to train the relationship between the body parts and object geometries. We share the same spirit with this approach. Specifically, we trained neural networks to predict natural human poses for a given desk configuration. Thus, when a designer changes desk configurations using our tool, he/she can view a responsive human pose automatically generated corresponding to the design changes.

3 FORMATIVE STUDY

We conducted a formative study to understand natural working poses. By conducting a *fly-on-the-wall* [63] at participants' homes, we observed various poses and grouped them into four groups. The results revealed that simple forward kinematics would not suffice to assist the design process, and we needed new strategies to design SmartManikin agency.

Procedure

We recruited four participants (3F, 1M) who use their desks for a variety of purposes (e.g., typing, watching movies, eating breakfast, etc). We visited their dormitory and observed their poses for three hours. The participants were acquaintances, so the presence of researchers did not influence their behavior. We videotaped the participants' poses, but also analyzed them in real-time during the observations. We made quick sketches and used them as material for a post-interview to understand their general thoughts towards the observed poses (e.g., Why did they take a certain pose?)

Results

We grouped observed poses into four categories: *comfortable*, *temporary*, *extreme*, and *ergonomic*. These four categories are not mutually exclusive. For instance, *comfortable* poses and *ergonomic* poses can be identical in a specific desk setup.

Comfortable poses are poses that last for more than 10 minutes. When starting a new activity, participants take a matching comfortable pose. For example, when P2 and P4 were typing, they tended to lean forward and put their elbows on the table, but when watching videos, both of them had their hands on their thighs and leaned backwards.

Figure 2: By observing various working poses at participants' homes, we proposed design strategies for SmartManikin.

Temporary poses are transitions between comfortable poses, and last less than three minutes. For example, P1 temporarily put both legs on the chair while P3 temporarily leaned forward and supported her head with her right hand when reading a book. These poses are not directly related to comfort, but people do them in order not to keep one posture for too long [8, 28, 36].

Extreme poses are poses that people do with maximum stretch, bend, or rotation. These poses were frequently shown when the participants needed to achieve a certain goal like grabbing a book from the highest or deepest shelf. These extreme poses depend on the user's height, body length, and available joint angles.

Ergonomic poses satisfy recommended joint angles such as neck or back angles. We observed that the participants tended to match ergonomic pose intermittently and consciously, such as stretching their back. In the case of P1, P2, and P3, they corrected their poses since the desks they used were too high, making their spine bend awkwardly.

Design Strategies for SmartManikin Agency

We generated design strategies by exploring the relationships between pose types and product design aspects (e.g., shelf height, etc). We describe our design strategies in detail with examples below.

Simulate multiple actions to inform real-life uses. The participants performed multiple activities from typing to reaching, similar to the results from Lee et al. [38]. Therefore, in order to support designers with possible use-scenarios during the design process, SmartManikin needs to switch among all the potential actions. *Temporary* poses can be excluded as they do not inform long-term usability, but including these can generate more realistic virtual humans in the future.

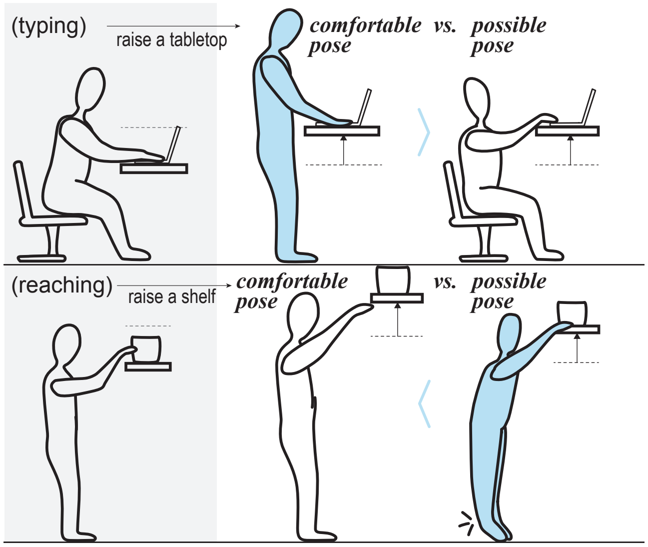

Figure 3: For SmartManikin Agency, comfortable poses should be prioritized over extreme poses in most cases (top), except for reaching actions (bottom).

Respond to real-time design contexts. Diverse aspects affect comfortable poses [41], including the configuration of the desk (e.g., the height of a desk) as well as the position and rotation of the co-use items with a desk (e.g., laptops, books, keyboards, etc.). Other aspects are related to personal preferences or sitting habits, such as "whether to use a backrest" and "whether to lean on the desktop". Therefore, the agency of the SmartManikin needs to intelligently respond to these aspects during the design process in real time.

Generate poses based on comfort, except reaching. In most cases, *comfortable poses* can help industrial designers estimate how potential users will likely behave with their product in the future. For instance, if a designer makes a desktop high enough, SmartManikin needs to stand up to remain in comfortable typing poses (Figure 3, top middle) even though it can reach the desktop while seated (Figure 3, top right). However, the reaching situation is exceptional. To let designers estimate a user's reachability, the SmartManikin needs to show how far its arm can stretch (Figure 3, bottom).

Simulate comfort and ergonomic separately. The results revealed the difference between *comfortable* poses and *ergonomic* poses (Figure 7). Figure 4 illustrates examples where the virtual mannequin is being simulated in a typing situation when the desktop gets raised. Concerning comfort, its arms will go up and its back will be leaned backward as illustrated in Figure 4, middle. However, to achieve ergonomic poses, the chair height should be raised in order to keep the mannequin's ergonomic posture as depicted in Figure 4, right.

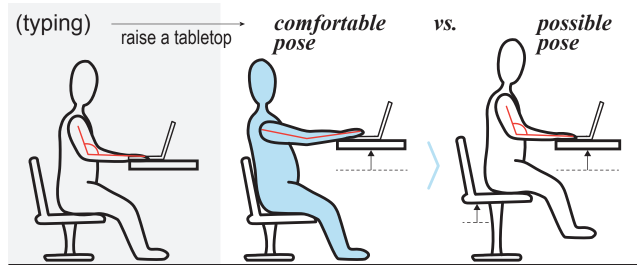

Figure 4: We decided to generate SmartManikin based on comfort (middle) and provide additional ergonomic pose feedback on the real-time body.

With the goal of providing natural behaviors of users, we aim to generate mannequins based on comfort and visualize healthy pose guidelines on the mannequin additionally.

4 POSE CAPTURE STUDY

In order to provide comfortable poses with a design tool similar to Grainger et al. [20], we captured the motions of 10 participants comfortably interacting with given furniture configurations, identified the key features of the poses, and then trained regression functions that output the features with respect to a given desk configuration. The SmartManikin's pose is generated from the estimated features using forward and inverse kinematics. Figure 5 shows the overview of this process.

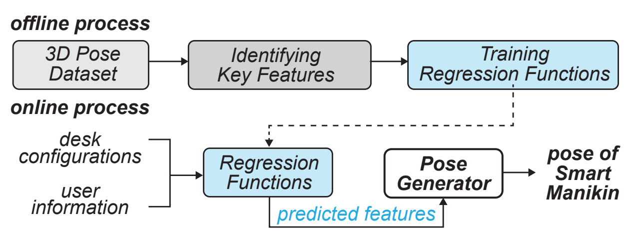

Figure 5: Overview of our pose generation system.

Conditions

Based on the formative study, we selected four aspects that affect pose generation. From those, we determined 10 conditions for a pose capture study, as shown in Figure 6. The four aspects we focused on are as follows:

(1) *Action type.* We selected four types of actions that were frequently observed in the formative study: reading, watching, surfing, and typing, as shown in Figure 6.
(2) *Desk height.* We tested various desk heights from *65cm* to *135cm* at *5cm* intervals. In the case of the *watching* action, we increased the height of the monitor instead of the desk to allow the participants to use the tabletop.

Figure 6: This figure illustrates 10 conditions used for pose capturing. We captured four actions (typing, watching, surfing, and reading) concerning sitting preference (using a backrest or not), lower arm positions (elbow supported or not), and height variations (desk height/monitor height). The poses were 3D captured with two Kinect devices.

(3) *Sitting type.* Significantly different sitting poses were taken depending on whether they used a backrest or not (named as sitting type). Other parts of the chair, such as the armrest or footrest, could affect the pose as well, but we assumed that their significance was minor and ignored them in this study.
(4) *Position of items.* Previous observations revealed that when people position their laptops near the desk's edge, they tend to extend their back and position their elbows in the air. Conversely, when they use the laptops farther from the edge, they tend to flex their back and elbows. To reflect this phenomena, we selected two positions for the items with 20cm distance, which is the average length of the lower arm (Figure 6).

Setup

We recruited 10 participants (5M, 5F, mean age = 25.8, SD = 2.15) who use their desks for more than six hours per day at various heights. For each gender group, we recruited people whose height is above average, below average, and average (M: 175cm, F: 162cm) in the local region.

In order to capture human motions, we placed two sets of Microsoft Kinect v2 so that they faced each other as shown in Figure 6. The Kinect devices were placed with care to avoid occlusion with the physical desk (Kinect A: height=1.74m, tilt=-18.90 degrees, Kinect B: height=1.84cm, tilt=-13.28 deg, distance between A & B = 5.19m).

The IKEA height-adjustable desk (BEKANT) was used to control the height of a desk. As shown in Figure 6 (setup), we installed a perforated metal plate in front of the desk to observe the participants' poses in real time while not giving the feeling of being watched. A measuring tape was attached to the metal wall to measure the height of the table.

Process

Before capturing motions, we obtained seven anthropometric measurements from each participant: heights of the elbow, shoulder, and eyes from the ground for both standing and sitting postures. Then we placed items (laptop, keyboard, and monitor) in target positions in advance (Figure 6-setup).

We asked the participants to perform specific actions (typing, watching, surfing, and reading) for each condition. The participants were not allowed to change the position of the installed items but were allowed to change their poses and the position of the chair. They spent as much time as they wanted to find a comfortable pose for a particular desk setup and were free to try several poses until they made a final decision. When they kept the same pose for more than 15 seconds, we made the desk 5cm higher and waited until the participants readjusted their poses. Each experiment was started from the lowest desk height, gradually approaching the peak height, and then returning to the lowest height.

We used a motion capture software package (IPI Motion) to obtain the participants' 3D skeleton data. The skeleton was estimated to be inside the participants' body shapes and were captured by the Kinect devices (Figure 8). All frames of the skeletal pose were saved in bvh format. We loaded the user motion bvh files into the virtual space and collected pose information, which were then used for identifying key features as described next.

Pose Feature Regression

We identified three key features for human poses: *base position*, *foot position*, and *leaning angles*. The features are independent of the participants' height.

Base Position As the height of the desk changed, the participants moved closer to or farther from the desk. In order to represent this movement, we obtained the pelvis position p_{base} in the transverse plane with respect to a reference coordinate frame T_{chair}. The frame T_{chair} is set at the initial position of the chair, so it is fixed with respect to the desk position.

Foot Position The second feature is the foot positions p_{feet} with respect to the pelvis frame in the transverse plane. When a person is standing, p_{feet} is more or less the offset from the pelvis to the hip joint, and for the sitting posture,

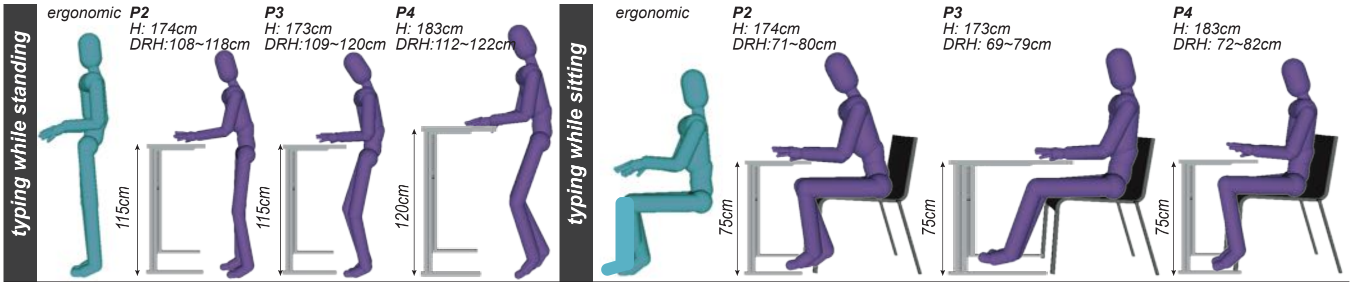

Figure 7: This figure shows typing poses at a recommended personal height for both standing and sitting. We revealed the gap between comfortable poses and ergonomic poses in real life.(H: participant height, DRH: desk recommended height)

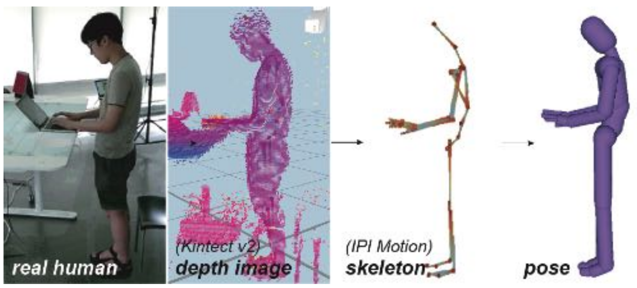

Figure 8: Pose capture process. Two Kinect devices obtain the depth images of a person, from which IPI Motion estimates the skeletal pose.

the magnitude of p_{feet} increases. To make the feature independent of a person's height, p_{feet} is defined as the foot coordinates divided by the participant's leg length.

Trunk Leaning Angle The leaning angle of the trunk highly depends on the desk height. Moreover, even at the same desk height, people may flex their trunk forward to view the monitor or backward to lean back. In order to model this behavior, we obtained the leaning angles of the spine joints θ. As our skeleton model includes three spine joints, this feature is a three-dimensional vector.

To generate comfortable poses with respect to the desk height, we trained neural network-based regressors that input the heights of the desk and user, and output the three features. For this, we divided users' sitting types into four categories depending on whether the backrest was used and whether hands were placed on the desk to lean forward, and trained separate regressor sets for each type.

The regressor set consists of three regressors, each of which estimated one of the three features. Each regressor was modeled as the multilayer perceptron, with one hidden layer of five cells, fully connected to the input and output layers. Sigmoid functions were used as activation function and the network weights were learned with the batch L-BFGS optimization method. It took around 30 minutes to train all of the regressors. Once trained, the average running time was extremely fast, around 0.2 milliseconds. The average sizes of training and test datasets were 26957 and 11552, respectively, per sitting type. The average error of the regressors on the test dataset was 2.1 percent.

5 SMARTMANIKIN

We implemented *SmartManikin* into a desk configuration system to simulate uses in terms of comfort. SmartManikin updates its poses based on high-level action commands received from a designer. When a designer changes the design parameters, SmartManikin predicts the most comfortable pose at a given desk configuration and responds to the changes in real time. Finally, ergonomic guidelines are additionally visualized on the mannequin to inform the designer of a ergonomic pose.

User Interface

The system interface contains a virtual mannequin, a configurable desk model, an item repository panel, and an action command panel as shown in Figure 9. During the design

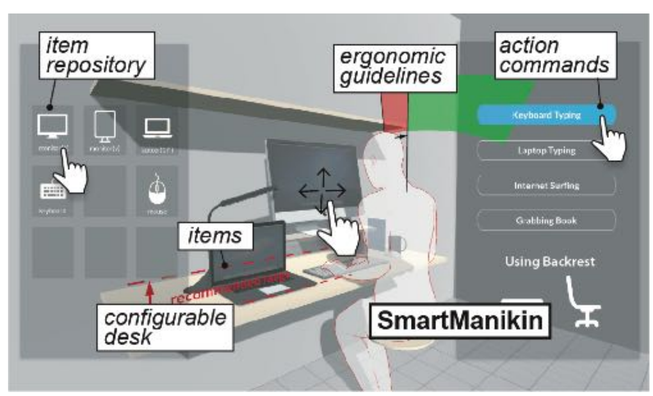

Figure 9: We applied SmartManikin on a 3D desk configuration tool, with a 2D interface.

process, designers can freely rotate the scene to view it from various perspectives, and zoom-in or zoom-out to check in detail. The geometry of the desk is parametric with parameters being "desk height", "desk depth", and "shelf height" and it can be customized in real time. The entire system was built in Unity3D.

The system enables four types of inputs from designers. First, designers can activate items from an item repository panel by clicking a target item (Figure 9, left), and they can also arrange or move items (laptop, monitor, keyboard, mouse, book, etc.) on the desk or shelves. Second, designers can simulate multiple use-actions by selecting from the action command panel (Figure 9, right). For example, they can shift actions between "watching" and "reaching a shelf" to compromise constraints between a reachable limit and a visible height range. Third, designers can assign preferred sitting poses (using the backrest or leaning on the desk). Finally, designers can apply design changes by altering pre-assigned design parameters, such as desk height, desk depth, or shelf height. They can simply change these parameters by dragging and dropping each desk part at a target position.

When the depth of a desktop increases, the objects on the tabletop need to stick to the desktop and move together. The SmartManikin stay at the same position until the desktop touches the mannequin; thereafter, the mannequin move backwards, similar to pushing interactions [48].

Agency Design: Responsive Pose Generation

Agency for SmartManikin was designed based on the strategies developed in the formative study. The SmartManikin agency generates poses at given desk configurations, item arrangements, and action command. The mannnequin's height and the leg length were 168 cm and 80 cm respectively. With the given desktop height and the mannequin's anthropometrics, the *features* are estimated by regressors described in the previous section. We used inverse kinematics and forward kinematics methods to generate SmartManikin's poses (Figure 10). We used a third party IK tool (Final IK) for inverse kinematics of the arms and legs.

Pose in relation to desk configurations. The SmartManikin agency generates poses in relation to real-time desk configurations. For example, when the designer raises the desktop height, the SmartManikin starts to stand up as shown in Figure 11. To do this, the agency first determines the base (pelvis) position p_{base} of the mannequin in the transverse plane. The T_{chair} is the reference frame at the default position of the chair, fixed with respect to the desk.

$$p_{des} = T_{chair} \cdot p_{base}, \tag{1}$$

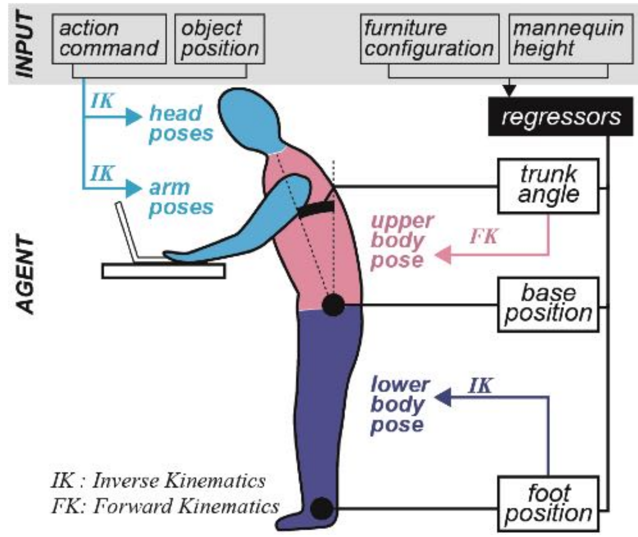

Figure 10: This figure shows the summary of SmartManikin agency design. The system first predicts three features, which are trunk angle, base position, and foot position. Then, the entire body pose is generated using inverse and forward kinematics using predicted features and user inputs. The effect of features and user inputs on the pose generation is color-coded in this figure.

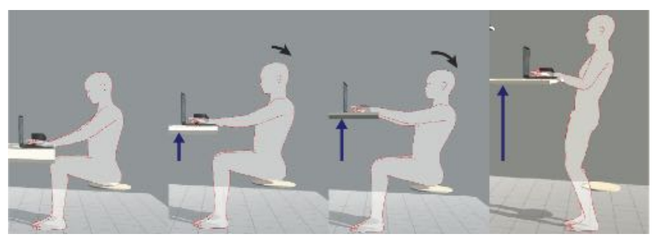

Figure 11: Examples poses that respond to design changes. If a designer raises a surface in the CAD model, SmartManikin updates its poses, and stands up in the end.

Then, the pose of the lower body was generated by the inverse kinematics that solves for the leg joint angles to realize the desired foot position f_{des}, which is obtained by multiplying the pelvis frame T_{base} with the predicted foot positions p_{feet}. As the feet are assumed to be on the ground, the height of the pelvis is determined trivially from the height of f_{des}.

$$f_{des} = T_{base} \cdot p_{feet}, \tag{2}$$

Finally, SmartManikin uses the forward kinematics to apply the predicted spine joint angle θ to determine the pose of the trunk. Using the procedures above, the SmartManikin

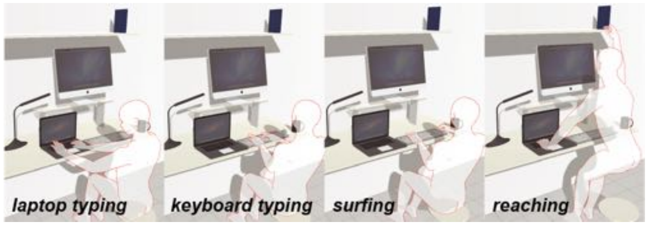

Figure 12: Sample poses that respond to behavioral commands. If a designer provides command, SmartManikin simulates the action within the constraint of design and context.

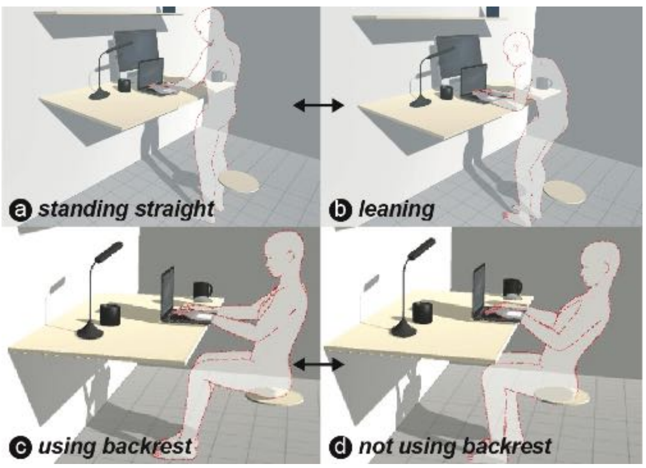

Figure 13: Designers can simulate different sitting or working poses at the same desk configuration. The top shows the difference between leaning and standing straight. The bottom shows the difference between using a backrest or not.

can generate poses except for the arm poses and the head orientation.

Pose in relation to action input and item arrangement. The SmartManikin generates poses for the arms and the orientation of the head as shown in Figure 12. Each pre-defined action is associated with a particular target item. For example, the keyboard is the target item of a “typing” action. The arm motions are generated by applying IK to place the hand on the target item.

Therefore, the arm and neck poses depend on the position or orientation of together-use items as well. For example, if designers push a keyboard deeper, then the SmartManikin should start typing while leaning on the desk with its elbows on the tabletop. Also, if they raise the height of the monitor, the back and neck will straighten up.

As described in the previous section, we used individual regressors for each sitting type so that the SmartManikin agency can respond to sitting styles as well. If the distance between a target item and the edge of the desk exceeds some threshold, it is assumed that the mannequin would place its hand on the desk to lean forward. Note that the estimated comfortable pose depends on the sitting type and thus may differ even for the same desk height (Figure 13).

Responsive Ergonomic Guidelines. When SmartManikin moves and acts based on comfort, ergonomic information are lacking. Therefore, we visualized ergonomic guidelines onto the body to inform designers about the target user’s recommended joint angles or visibility range for healthy poses.

6 EXPERT EVALUATION

We aimed to get early feedback from professional product designers, the potential stakeholders of our system. We recruited three furniture designers who each have more than eight years of experience: One makes custom-made designs (P1, M, age=40), another designs mass-produced furniture (P2, M, age=36), and the last one is an expert in DIY and furniture hacking (P3, F, age=43). We also recruited a fashion item designer with 11 years of experience (P4, M, age=35) to discuss how our system could be applied to other product categories.

Procedure

We started by explaining the concept of SmartManikin in conjunction with the interface, interactions, and design strategies. We demonstrated our system on a touch screen PC (Dell). All of the experts tested our system for about 5-10 minutes with no conditions (to derive an informal but rich discussion) prior to the interview and kept testing it freely during the discussion. Then, we conducted a Focus Group Interview (FGI) to discuss our concept, design strategies, interactions, and system usability. They reflected on their previous design cases to discuss how SmartManikin could have been helpful for them. We summarized the key feedback from this initial evaluation study.

Expert Feedback

In general, all the professional designers used our system easily and got familiarized with the SmartManikin interface within a short amount of time. A few minutes later, they felt emotionally attached to the virtual mannequin and regarded it as a virtual assistant.

The expert designers appreciated the *comfortable* and *natural* motions that SmartManikin generates. P1 commented that whenever he designs a chair, he spends a considerable amount of time observing people’s natural sitting poses in the field and uses those poses as design references. He mentioned, *“Previously, I always had difficulty storing natural human poses into a 3D format (mostly done by sketches), but in the future, SmartManikin can alleviate this problem.”*

Figure 14: We evaluated SmartManikin with four professional industrial designers. We let them use our system then conducted a FGI to discuss the potential of our concept.

All the furniture designers agreed that SmartManikin could be valuable in the *early stages of design*, especially when prioritizing or compromising among design constraints. P2 commented, *"A bunch of things need to be considered when deciding the depth of a table, such as the monitor size, reachability, space clearance, and sitting pose. SmartManikin can help me find out the interrelationships between them by simulating with human poses."* P1 highlighted that he wants to define approximate dimensions or volumes of an item using SmartManikin, then use those brief volumetric plans as design constraints. On the other hand, P4 mentioned that dynamic human poses are not significant when designing fashion items such as bags in the early stage. They prefer static poses with detailed body skeletons, for example, accurate hand poses while holding a suitcase.

All the expert designers valued SmartManikin as a *real-time evaluation tool* as well. To evaluate their designs, they made mock-ups and used their bodies to test multiple scenarios. But they had some difficulties since their bodies could not represent those of their clients, especially when designing a chair for a cellist (P1) or a bag for teenagers (P4). For this reason, professional designers appreciated SmartManikin for helping visualize future use-scenarios within the digital space. Still, they requested more features such as visualizing muscle pressure or the level of comfort.

Moreover, the designers discussed the potential for using SmartManikin as a *communication tool*. They usually draw the human silhouette when delivering their design to clients or colleagues in order to share the potential use-scenarios. They found SmartManikin to be a good alternative that would be able to support designers in sharing intended uses with other stakeholders.

They agreed that generating the mannequin based on comfort rather than ergonomic is a good strategy. P4 said, *"I enjoy looking at how the mannequin turns into a better pose throughout my design process."* P1 also shared a similar opinion. Although the experts were all aware of basic human factor guidelines, such as the recommended monitor height or ergonomic sitting positions, they valued that the related information was situated on the spot. This made them aware of the ergonomic impact easily.

The furniture designers pointed out that one possible shortcoming of the current SmartManikin is *a third-person perspective*; thus it is hard to understand the user's perspective. P1 mentioned, *"If I design a TV stand for a living room, I will let the mannequin sit on a couch and look at the TV. But in that case, I want to share the mannequin's line of sight to decide on the height of the stand. Can you shoot a ray from the mannequin's eyes?"* Conversely, the bag designer was satisfied with a third-person view, and did not express a need for the first-person perspective.

The expert designers shared other application scenarios and additional functions that SmartManikin could benefit from. All agreed that kitchen counters could be a good option as they require multiple actions, such as washing the dishes, reaching the shelves, cutting vegetables, or stirring pots. In addition, the bag designer mentioned that it would be helpful if the mannequin showed possible handling, wearing, and grabbing actions for his bag design. Furthermore, it could be valuable for designing public spaces, such as park benches or cafe tables with the support of multiple mannequins. For this, the experts requested smart simulations for the movement of the mannequins as well as smart posing.

7 DISCUSSION AND FUTURE WORK

In this paper, we introduced SmartManikin, an autonomous virtual mannequin with agency that responds to real-time design changes and commands. We made the first step to inform usage information with respect to ergonomic as well as comfort within the digital design tools. In order to convey comfort, we systematically captured natural human poses, trained these poses, and simulated them within an interactive design system in real time.

However, our research has several limitations. First, the SmartManikin's poses were generated from the collected skeleton data; therefore additional features such as body physique or anthropometric information were ignored. Second, pose data used for training our SmartManikin system was collected during a short-term period and did not include long-term comfort. Furthermore, we only applied our concept to a desk configuration task with limited design freedom. Nevertheless, feedback from professional industrial designers proved the potential of SmartManikin in terms of supporting efficient and engaging design experiences. In this section, we reflect on our research, discuss our insights and share possible implications for future work.

The Role of Digital Humans in the Design Process

We originally proposed SmartManikin to support the design process from the *conceptualization stage* (e.g., brainstorming the purpose of the product) to the *evaluation stage* (e.g., confirming the intended use of the product). Although design evaluation, especially for usability aspects, has been mostly done in the latter stages of design, our system can provide an early preview by simulating design-responsive poses, thus promoting iterations between exploring and evaluating [53].

However, in the evaluation study, the professional designers confirmed the applicability of SmartManikin not only as a generative and evaluation tool, but also as a communication tool for designers, clients, and possibly for potential users. For instance, by generating expected human motions accordingly, the applications for online shopping or personal fabrication can deliver use-aspects (e.g., a mannequin family watching TV on a sofa). In addition, furniture designers also commented on the potential of our system in the alternative early-prototyping stage.

Beyond supporting traditional design processes, digital humans with natural poses can be used as design resources in the generative design process. Future design systems could generate optimal designs automatically based on the digital human poses to make a design fit real-life uses and scenarios.

Informing Comfort and Health

Capturing *comfortable* poses in the field (Figure 6) and using them as our training set enabled us to simulate natural and realistic human poses in relation to design output. However, when we captured the poses, we did not differentiate the level of comfort at each setup; therefore our system could only inform the most comfortable poses without telling how much comfortable it is. Providing information about the degree of comfort and health on the virtual human could be the possible next step (e.g., a heat map on the body to visualize comfort levels).

In order to inform both comfort and health, we visualized them in two separate ways (posing strategy & ergonomic guidelines) although they are highly related to each other [45]. Our research confirmed this approach is good in design applications as professional designers mentally treated them differently; “comfort” as *users’ satisfaction* and “health” as *designer’s capability*. The professional designers mentioned that reponsive poses helped them convey *user’s perspectives* in the design process and were satisfied that they have the power to find their own design.

Personalization of Virtual Human Agency

The personality of virtual mannequins, such as a persona, should be carefully considered when designing virtual humans. Although we did not include any personal aspects, professional designers felt attached to the mannequin and regarded it as a personal assistant or as a virtual client. To enhance their design experience, we need to further investigate the relationship between a virtual human and a designer, classify different types of client personalities (e.g., expressive, passive, picky) and activate proper agency accordingly.

Similarly, the professional designers requested a feature that enables them to customize virtual human agency to fit their target group. We argue that the target group goes beyond anthropometrics, age, job, habits, and corresponding joint limits. Future systems could target specific user groups such as cellists, kids, or elderly people with arthritis. For a particular type of product such as youth furniture, chronologically or concurrently simulating the journey of growing would be appreciated.

Applicability in Other Human Interactions

In our study, we applied a virtual mannequin with agency to furniture design tools; however it can also be applied in other domains, such as hand-held products (bags, tools, or cups) as well as interior designs. Although we focused on full-body poses, future agency of virtual human could enable zoom functions and simulate elaborate hand poses in relation to product elements [33]. For example, based on the work of Rachel Eardley [10, 11], it would be feasible to generate hand grips and body postures for mobile phone use and make mannequins react to UI design choices such as swiping, typing, or UI layouts.

In addition, although our current SmartManikin only changes poses, simulating the movements within the space with the considerations of “multi person scenarios” or “space efficiencies” [62] could be a possible next step. Building upon the work in building performance crowd simulations [13, 51], we can generate natural human behaviors and movements based on real-time building or space layouts.

Finally, virtual humans can be presented in other platforms as well, such as virtual reality (VR) or augmented reality (AR) applications. For example, as a novel type of “AR manual,” the virtual mannequin can show how to use the product by simulating the use.

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