Interactive and Situated Guidelines to Help Users Design a Personal Desk that Fits Their Bodies

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Figure 1. How can we design a desk that fits our bodies and needs? We explored interactive ergonomic recommendations for personal design applications. We developed a desk design system in VR, and evaluated it with six users through DIY design and the use of custom fabricated desks.

ABSTRACT
In this paper, we explored the application of human factor guidelines in personal fabrication. This is useful for several Do-It-Yourself (DIY) scenarios, including users adjusting workstation configurations or designing a desk to fit a single person. We identified a dependency map between the user's anthropometrics, ergonomic pose recommendations, and design dimensions. Based on this, we developed situated and interactive guidelines to assist users in design applications. We applied these guidelines in a Virtual Reality (VR) system that lets users customize their desk and provides real-time feedback and feedforward on pose and design. We evaluated the system with six participants, had each one design a personal desk, fabricated their desks, and let them work on their desks for four hours. The design and evaluation contribute to fabrication tools as it helped users be aware of their pose and ergonomic knowledge, and design for their bodies and needs.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g. HCI): Graphical user interfaces.

Author Keywords
personal fabrication, interactive guidelines, DIY

INTRODUCTION
Emerging technologies in *parametric design*, *personal fabrication* or *DIY toolkits* provide new opportunities for people to make products according to their specifications [28]. People take on a new role as both designer and user when they design objects for themselves. In this paper, we look into how to support people designing personal products that fit their bodies and needs.

Our motivation is based on casual observations of how people estimate comfort or good posture when buying furniture in offline stores. People test comfortable poses and simulate their use, not unlike designers employing experience prototyping [6]. They also gather information from experts, such as asking family members to measure the height up to their hands when holding a pose [31], or hiring ergonomists to adjust office desks [24]. This observations shows that selecting, adapting, and designing furniture is a process that includes information gathering and prototyping to understand personal fit, and the body plays a central role. However, those play-acting activities are difficult to perform when shopping online or using CAD or mass-customization tools. Also, personalized advice on ergonomics is an under-explored topic in personal fabrication tools.

For this reason, we looked into design guidelines that deal with the personal fit of a product. The field of *Human Factors* provides recommendations for product comfort and safety.

However, these guidelines are either aimed at professional designers who design items to fit a population of users, or at ergonomists who evaluate and recommend good postures. In this paper, we made a first step in making these recommendations applicable for personal design, and related anthropometrics, ergonomic pose recommendations, and design parameters in a dependency map. The result is a set of guidelines that provides both feedback and feedforward on design and pose.

We made these guidelines applicable for interactive design systems. Guidelines are generated based on the user's body, posture, and pair-use items, and dynamically respond to users' real-time design choices or actions. For example, if a user changes the seat height, the recommended desk and monitor heights update accordingly. Likewise, if the user makes the tabletop deeper, the shelf reachability guidelines are also updated. We implemented these guidelines in an office desk customization system: Body2Desk, that employs motion-capture and Virtual Reality (VR). We evaluated Body2Desk with six users and let them design their desk. We fabricated their desks then let them use their desk for a few hours. The results indicate that the system makes them aware of ergonomic guidelines and lets them effectively employ them. We discuss the benefits and uses of guidelines in a personal design process, and applications for future fabrication interfaces.

We selected the office desk as an application for this research because it interacts with the entire body and consists of a complex set of recommendations including pose as well as use efficiency, such as reachability. In addition, the use of computer workstations is commonly reported to contribute to back and neck pain. Also, an office can be customized by users through several fabrication services such as *Opendesk* [40], or additional accessories like monitor stands or shelves. However, the insights or interaction techniques derived from this study are not limited to desks, and can be applied to other types of products such as kitchen bars and bookshelves, or to services like furniture arrangement.

There are several limitations to this work. We employed a Kinect v2 for motion capture which has known problems with accuracy [8, 67]. We derived ergonomic guidelines from literature [7, 27, 42, 43, 61], and applied them in a novel, but untested way. By situating and visualizing human factor guidelines in design tools, we limited our focus to 1) the education of good body poses, and 2) workplace intervention. We do not claim that this approach solves discomfort or prevents musculoskeletal disorders; however, it might be part of a future solution.

This paper makes three contributions: 1) Personalizing human factor guidelines with a dependency map that relates anthropometrics, pose, and design dimensions, 2) Design considerations that deal with interaction techniques for informing guidelines in VR fabrication tools, and 3) Body2Desk system implementation and user evaluation.

RELATED WORK

Our research bridges existing work in physical ergonomics with design tools for non-professionals (casual users).

Active Posture Measuring

Musculoskeletal disorders, such as back pain caused by office work, are a common but important problem. Research in HCI has focused extensively on active posture measuring and feedback. Some projects monitor upper body posture with body-worn sensors [34, 64] or with sensors embedded in furniture, such as in chairs [38]. Other projects employ cameras [57]. Real-time feedback on posture is provided in various ways: in apps and on displays [64], through physical feedback [16] such as a bending plant, vibrotactile actuators in a chair [69], augmented mirrors [1, 57] or co-workers alerting each other [50]. These systems aim to assist users in maintaining good posture over time; however, they do not consider configurations of the workspace in conjunction with their pose.

Ergonomic Knowledge and Application

The optimal workplace setup is highly dependent on the task, and prolonged postures need to be avoided [35]. Modern office equipment is designed to adapt to the users' anatomy and needs, such as with highly adjustable chairs or configurable table heights. However, chairs are often not adjusted by users, or not adjusted to the optimal position [14, 60, 62].

Several books inform users and designers about ergonomics with practical guidelines [7, 27, 42, 43, 61] and are discussed in the next section. Education and training programs are popular approaches in companies [20], but their effectiveness is debatable [56]. Some studies show that ergonomic knowledge does not always lead to action [53] whereas other studies indicate that users changed their work practices and were able to adjust their workstations effectively [46]. Combining ergonomic furniture with office ergonomic training programs [20], on-site interventions by ergonomists [24] and follow-up was found to be effective. In this paper, we focus on education and interventions as we situate and personalize ergonomic guidelines for users who are designing and adjusting their own desks.

Interactive Simulation in Design

A large body of work on HCI aims to make geometric modeling accessible to non-professionals [12, 23, 37, 48, 65, 51]. One problem is how to ensure that the design can be made, and whether it functions as expected. Therefore, researchers recently started to include interactive physics simulations in the modeling application, to ensure the design is valid [51], stable [48] or structurally sound [59]. Sketchchair [48] for instance, lets users sketch a chair with a few strokes and generates fabrication-ready design drawings. Reference objects and a poseable mannequin help users estimate the size of the chair, and rigid body simulations predict stability. Umetani et al. [59] provides suggestions on the stability and durability of furniture based on an interactive physics simulation of the joinings between planks. Providing feedback and feedforward on the design helps users make decisions. We build upon these works but focus on ergonomic guidelines to help users design for usability, comfort, and health.

Ergonomic Simulations for Evaluating Designs

CAD systems with built-in ergonomics assessment capabilities are used to simulate complex tasks to analyze postures, forces,

Body	***Body Posture (health)***		ex. The angle between the thighs and the torso should be greater than 90 degrees.
	Body Activity		ex. For comfortable typing, the height of the desk should be 25-30cm above seat. ex. For standing worker, the room for the feet should include toe and knee space to move up close to the working surface.
	Body Clearance		ex. The clearances between the seat surface and the underside of the table should anthropometrically accommodate the thigh clearance of the person.
	Body Reachability		ex. For comfortable reach, the height of the shelf should be within the reachable range when the user is standing in front of the desk. (Maximum Shelf Height)
Object	***Object Efficiency***		ex. To design efficient and flexible storage area around a workplace, key operating objects should be in a reachable area.
	Object Use	***Visuality***	ex. The position of the monitor should be at about eye height, and keep a distance of more than 30cm from the eyes.
		Input Motion	ex. Ideally, your keyboard and mouse should be shoulder-distance apart and as level as possible.
Space	***Space Clearance***		ex. It is important to consider the circulation zone requirement for passage behind the seat at the typical workstation.The edge of this zone should take into account the movement of the chair within the chair clearance zone to avoid obstruction of any people circulation behind it.

Table 1. We collected 68 human factor recommendations related to office work, and grouped them into three categories: body, object, and space.

collisions, and visibility. Jack [4] for instance, is a virtual human model that supports anthropometric scaling, mass, and joint-limit information for given populations. Other systems let users evaluate virtual designs in Virtual Reality [2], such as automotive interiors or accessibility in factories. Although some authors reported on the advantages of co-designing ergonomics with users [15], professional ergonomics tools are used to evaluate designs to fit a population, not to generate designs for, by, or with a single user.

Rehabilitation, Sports, and Skill

Third-person feedback on pose and motion is widely used in sports training and rehabilitation. Biomechanical analysis helps optimize particular movements or adopt new techniques. Motion Capture and Augmented or Virtual Reality provided advantages over traditional video playback, as they can be real-time, situated, interactive, and allow multiple viewpoints. Marker-less motion tracking with a depth camera such as the Kinect v2 sensor is commonly applied and has advantages over systems that require markers or sensors placed on the user's body [8]. Since the Kinect was developed for playing games, the accuracy is best when facing the sensor and standing, and upper body joints are identified with less error than lower joints, especially in sitting poses such as crossed legged [67].

Various systems provide real-time, third-person avatars for training, providing feedback on poses and feedforward on how to move [1, 18, 45, 49, 58]. Other systems employ augmented reality to annotate the real world with instructions or feedback on motion [17, 52, 54]. Laplacian Vision [22] predicts the motion path of a bouncing ball and visualizes its trajectory in the Hololens. We build upon these works and included virtual avatars to provide real-time feedback from multiple views.

Design for and with the Body

Systems that let users design for their bodies have to deal with the challenges of dynamic and complex geometries. Therefore, some systems let users design directly on or with their bodies [13, 47, 68]. Lee et al. [30] let users simulate actions and pose to design furniture that fits their bodies and uses. To solve reachability issues, for instance when designing shoes or hats, other systems use a mannequin [66], or let users temporarily step out of their bodies [68]. However, most systems use augmented mirrors [10, 63]. Although these systems embody the design task, as far as we know, situated ergonomic guidelines have not been explored in a personal design context.

Augmented and Virtual Reality

Wearable displays (such as HMDs) let users design virtual objects real-scale, immersed or situated. For instance, Yee et al. [5] let users sketch objects in Augmented Reality, and Lau et al. [29] presented a system that composed objects out of primitive shapes. Instead of generic design tools, we focused on variant design [41] as we let users configure a parametric model. Designing in-situ brings similar challenges as designing on the body, as these interfaces do not support multiple or scaled views. In order to achieve an overview of the design, some systems provide a second miniature representation [55, 44], while others let users step back [30]. We employed both in our design.

GUIDELINES FOR PERSONAL COMFORT AND USE

In this study, we limit our focus to an office desk. We collected design guidelines for desks from various fields: human factors [27, 43, 61], working postures [7], furniture design [42], government regulations [21, 3], and furniture companies [25, 11, 36]. Guidelines aimed at industrial designers are mostly to fit a large percentage of an intended user population, and are indicated as a range, for instance, from the 5 percentile to the 95 percentile (e.g., *the desk height should be 610mm-711mm from the floor*). Guidelines for ergonomists are for observing people's poses and defined as angles (e.g., *the monitor should not be located lower than 45 degrees from eye level*). Both guidelines are not directly applicable in personal design tools that provide interactive design recommendations. Therefore, we first grouped the collected guidelines into three categories as shown in Table 1: related to body, object, and space.

Body-centered guidelines are related to anthropometrics and pose (Table 1-body). Several guidelines aim to prevent back and neck discomfort and carpal tunnel syndrome through good *posture*. These are typically measured as the angle between

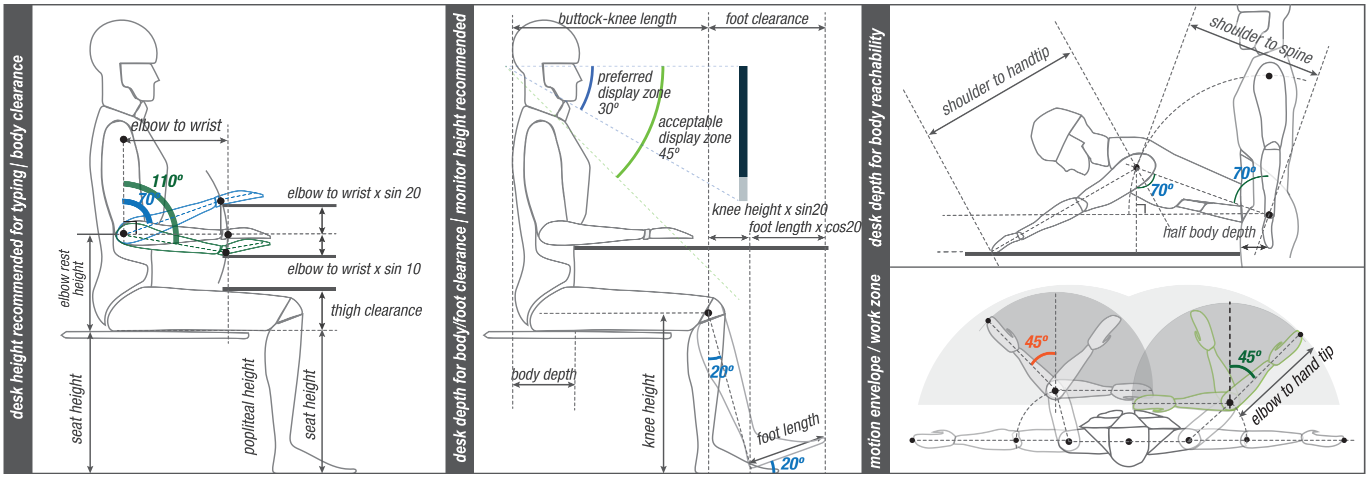

Figure 2. We redefined ergonomic guidelines for a single person and a desk; and we used anthropometrics and recommended angles for good posture.

connected bones in the sagittal plane. A second set of guidelines provides recommendations for specific *activities* such as typing or crafting. Third, *body clearance* deals with the distance between the body and the desk, while *body reachability* illustrates the limits where the desk can be used comfortably concerning the user's reach with their hands.

Object-centered guidelines are related to the objects that people use on the desk, such as a monitor or a keyboard (Table 1-object). Some inform users how to use objects *efficiently* and deal with the arrangement and reachability of frequently used items. (e.g., recommended motion envelopes are presented in the transverse plane with primary and secondary zones.) Other recommendations involve the correct *use* of objects (e.g., the height of the screen to maintain good posture while reading).

Space-centered guidelines deal with the desk in relation to the office environment. For example, the user needs to consider the minimal distance between the chair and the walls to move around freely. Proximity to other furniture (eg. the distance between the desk and storage closet) should also be considered to maintain efficient usability.

Guidelines from Population to a Person

There are no guidelines for furniture dimensions and ranges based on a single person's anthropometrics and pose. Therefore, we reverse engineered furniture guidelines from the recommended pose guidelines. For instance, there is a rule that "*good posture for typing is defined as sitting straight and keeping the elbow angle between 70 to 100 degrees,*" as illustrated in the Figure 2 on the left. We personalized the rule with seat height, elbow rest height, length between elbow to wrist, and the recommended elbow range, as shown in Equations 1 & 2.

$$\min h_{typing} = h_{seat} + h_{elbow\ rest} - l_{elbow,\ wrist} \times \sin(90 - 70) \quad (1)$$

$$\max h_{typing} = h_{seat} + h_{elbow\ rest} + l_{elbow,\ wrist} \times \sin(100 - 90) \quad (2)$$

TYPE	*SAMPLE GUIDELINES*	COROLLARY PERSONAL VARIABLES (*static, dynamic*, body, object, desk parameter*)
Body Posture	Proper back /neck angle	*back angle*, neck angle*, monitor height*, desk height**
Body Activity	Recommended desk height for typing (sitting)	*elbow rest height, elbow-wrist length, seat height*, proper elbow angle, tabletop thickness*
	Recommended desk height for typing (standing)	*elbow rest standing, elbow-wrist length, proper elbow angle, tabletop thickness*
	Recommended monitor height	*sitting eye height*, seat height*, proper display angle*
Body Clearance *(sitting)*	Desk height clearance	*thigh clearance, seat height*, desktop thickness*
	Desk depth clearance	*knee height, foot length, buttock-knee length, body depth*
Body Reachability *(sitting & standing)*	Desk depth reachability	*desk height*, shoulder-fingertip length, spine height, shoulder-spine length, body depth,*
	Shelf height reachability	*desk depth*, shelf depth*, shoulder height*, shoulder-fingertip length, body depth, shelf thickness*
	Shelf depth reachability	*desk depth*, shelf depth*, shelf height*, shoulder height*, shoulder-fingertip length, body depth*
Object Efficiency	Motion Envelope	*sitting position(x)*, elbow-fingertip length, shoulder-fingertip length, primary working angle*
Space Clearance	Chair clearance	*desk depth*, chair depth*, space (wall)*

Table 2. The dependency map illustrates how the design relates to anthropometrics, ergonomic pose, design parameters, and pair-objects.

These rewritten guidelines define ranges of recommended furniture dimensions and can be applied in personal design systems. For validation, we tested the new rules with two anthropometric indices (the fifth and 95th percentiles). When we applied our rules, the recommended ranges matched the lower and upper recommendations of the rules that fit a population.

Dependency Map for Personal Guidelines

Because dimensions and guidelines are related to each other, *e.g. the recommended tabletop height is dependent on the seat height*, we made a dependency map. As shown in the Table 2, a user's body measurements, joint position, pair-use objects, and desk dimensions all influence the guidelines.

A few rules depend on static variables that do not change, such as the length between the body joints. However, most of them need to respond to a user's real-time dynamic posture, actions or design decisions. For instance, the recommended tabletop height should be updated when the user changes the height

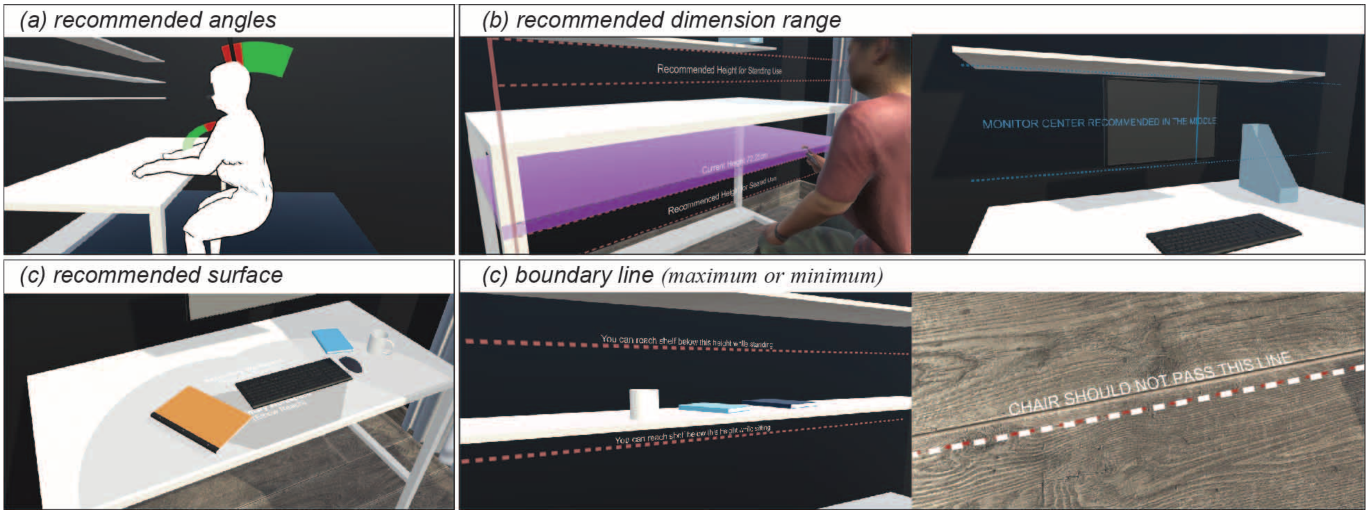

Figure 3. Different visualization approaches are required for each type of guideline. Good posture is described as an angle range and can be situated on the body. The recommended range can be illustrated with two lines on the spot, while reachable maximum guidelines can be drawn as a single line.

of their seat. Also, the desk parameters affect guidelines; for example, desk height relates to the reachability of shelves.

The dependency map also revealed conflicting dependencies between guidelines. For example, the desk depth is not only related with the tabletop itself, but also with shelf reachability. In such cases, presentation is important. Currently, we provide all the related guidelines and the user has to balance or compromise between the rules to make decisions.

DESIGN CONSIDERATIONS

In this section, we explore several design considerations for responsive and situated guidelines for interactive design systems. We highlight four: *visualization*, *feedforward and feedback*, *context-awareness*, *visualization*, and *point of view*.

Visualization

The guidelines can be provided in several ways, such as with haptic feedback. In this paper, we focused on the visualization techniques as we were inspired by the seminal book by Dreyfuss “Human Scale” who overlaid dimensions on bodies in poses, which allows to situate interactive guidelines in-place [9]. Related design interfaces that provide users with suggestions visualize design options separately on extra panels [59, 39, 19], or provide parametric design sliders with illustrations of recommended ranges [26], as it is difficult to show alternative 3D geometries in-place at the same time. By situating the guidelines near the design parameter, the users can be aware of information while making design decisions.

Guidelines regarding *posture* of the back, neck, or elbow are visualized in the form of an arc. We drew the angle range directly on the real-time body, as shown in Figure 3a. Also, the recommended range for a dimension (e.g., the recommended height of the desk or monitor) is represented with two lines and a plane in between (Figure 3b). Similarly, the *motion envelope* for object efficiency is illustrated with a highlighted surface and directly shows their primary and secondary working zones. Other guidelines are represented as a line on the limit for that dimension (Figure 3d), so the user can understand where the maximum height or depth they can reach.

In addition to these guidelines, simulation such as collision detection between furniture and the virtual body could limit a range. For example, when the user tries to lower the height of the desk below the body clearance height, the height remains unchanged at the minimum value.

Feedforward and Feedback

As guidelines are dependent on body, pose, and objects, they need to be responsive. First, guidelines provide interactive *feedback* [9] on users’ posture changes or design decisions. For example, when people make the depth of a desk too deep, the system informs the user that the back of the desk is not reachable. Also, when users assume an unhealthy posture, the guideline warns them, such as their back leaning forward too much (Figure 4, top left).

Guidelines also provide recommended ranges with *feedforward* [9] interaction, which tells users the ergonomic impact of their design decision in advance. For example, guidelines indicate a range of recommended table heights, or show recommended neck, wrist, or back angles. Feedforward suggests proper posture and dimensions while designing the desk.

Context-Awareness and Dynamic

Some guidelines are context-dependent. For example, the recommended desk height for typing is different from those reading a book or writing on paper (Figure 4, bottom). Therefore, the system needs to discern a user’s prime needs based on their behavior and visualize the guidelines accordingly.

Other guidelines are activity agnostic. For instance, designing the shelf heights needs to take into account both sitting and standing reachability, and both ranges should be shown at the same time. In addition, as users use their bodies for both designing and simulating, certain guidelines do not need to be responsive to the changes in posture when switching from

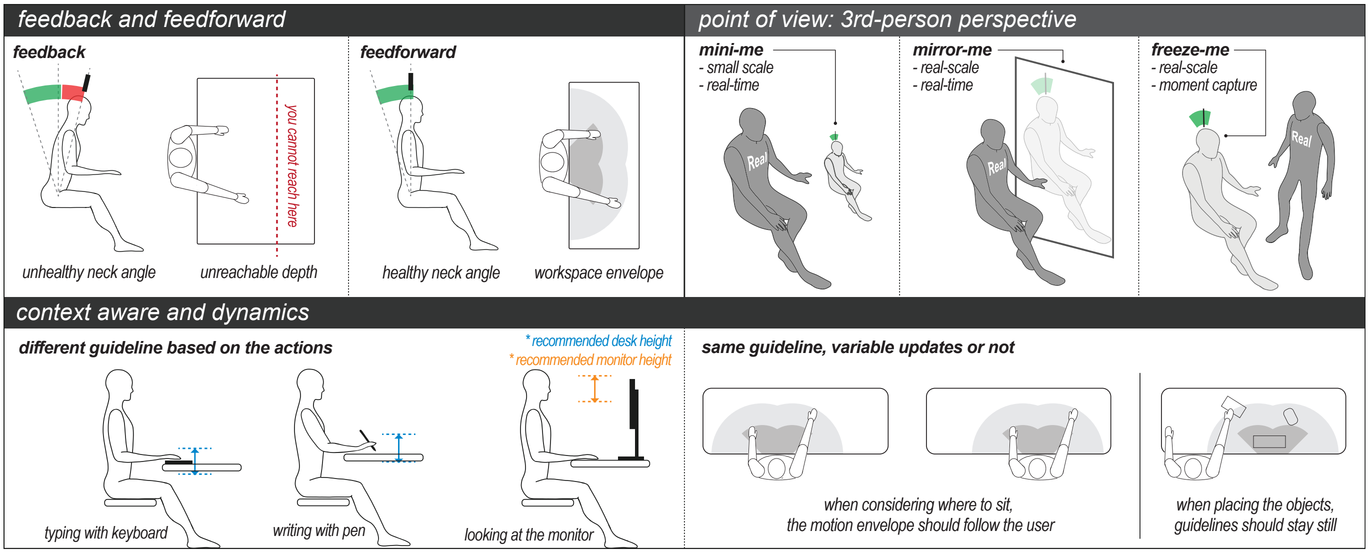

Figure 4. (top left) We provide interactive feedback on user's posture changes or design actions, and provide feedforward to show the design space and recommendations. (top right) To support third-person views, we explored avatars that copy the user's actions in time or space.

posing to design activities. For example, the motion envelope that indicates primary and secondary reachability depends on the user's position. However, when the user moves around to arrange virtual objects, the motion envelope should be frozen in the default sitting/standing pose (Figure 4, bottom).

Point of View

Designing with the body and from a first-person perspective engages users in their designs and relates their design to their needs [6, 30]. However, as people cannot see their entire body, feedback on poses is better achieved from a third-person perspective. Therefore we designed two principal ways of providing feedback: in space and in time (Figure 4, right).

The advantage of feedback in time is that the body is visualized in place and on a real scale. *Freeze-me* captures a user's pose and lets them step out of their body to examine their pose in relation to their furniture design. The advantage of feedback in space is a direct feedback on the pose while interacting with the furniture. *Mini-me* is a scaled-down avatar that can be freely positioned and oriented as any other virtual object. In that way, users can examine their pose from various angles, and move the avatar in their line of sight when posing and acting. *Mirror-me* is similar but on a real scale. By looking sideways, users observe the angle of their back and arms.

BODY2DESK

The guidelines we described in the previous sections can be applied to multiple types of interactive design systems. As an example, we developed a prototype in VR as it provides an embodied, first-person view on the design task. Body2Desk lets users customize the dimensions of a parametric desk model to their specifications by prototyping with their bodies, and provides guidelines according to the uses' pose and actions.

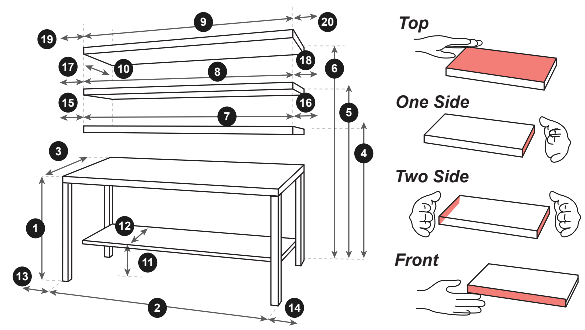

Figure 5. The parametric desk used in Body2Desk has a tabletop, footrest below, and three shelves. The position and dimension of each surface can be customized with gestures or voice commands.

System Design

Based on a typical work desk design, we prepared a parametric desk with a tabletop, a footrest, and three shelves, which can be defined with 12 parameters (Figure 5). Similar to Lee et al [30], we employed a combination of full-body gestures and voice commands. Immersed in a VR environment, users can act freely, move around in the design space, position virtual objects such as monitors or books, and set dimensions by saying *"Desk height, until here."* Voice commands were useful when users were posing and acting, or specifying dimensions with body parts other than their hands, such as their feet. However, we found that hand gestures were preferred for positioning objects. For completeness, we also implemented hand gestures for changing dimensions. We employed pinch gloves [33], and let users grab or drag a surface to manipulate dimensions (Figure 5), as well as the virtual props. An undo feature was provided with a voice command, *"undo."*

To provide a third-person perspective on the users' poses in VR, we implemented two virtual avatars: *Mini-me* and *Freeze-*

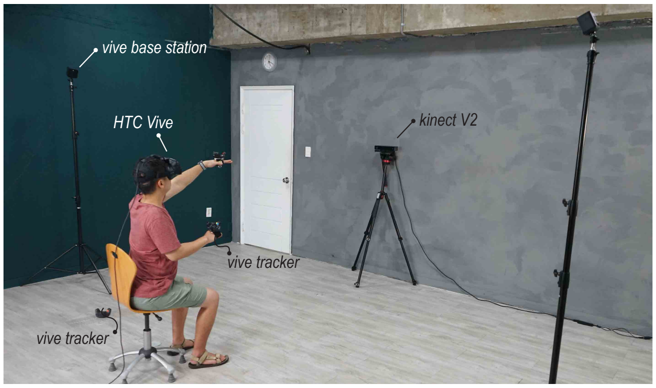

Figure 6. The user wears an HMD and a Kinect captures the user's pose. Two 3D trackers were attached to hands for pinching interaction, and 3D tracker was attached to the chair to capture the seat height.

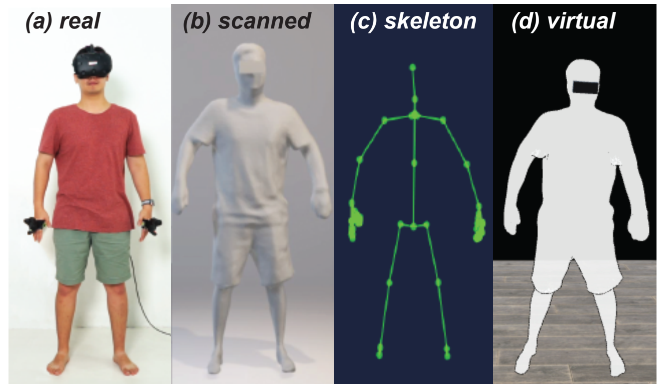

Figure 7. The user's body(a) was 3D scanned with a Kinect (b), and the skeletal joints were captured (c). Those were combined to generate a virtual human avatar, and a toon shader was applied (d).

me, based on the users' 3D-scanned bodies (Figure 1). Mini-me can be manipulated with gestures, same as manipulating the virtual props. Freeze-me was not able to move or rotate, but can be activated with voice command, *"freeze."* We generated human factor guidelines based on each user's anthropometrics (from the scanned body) and joints (captured in real time) as shown in Figure 2. For our system, we selected guidelines which were frequently mentioned in the literature (Table 2), and suitable to be captured in the Kinect. The goal of this study was not to provide accurate and complete set of guidelines, but to observe how people use interactive guidelines in their design process.

We followed the design considerations previously described, and made the guidelines context-aware with feedback and feedforward. Our system only activates the guidelines that are related to the parameter the user is changing (Table 2). For example, when the user is adjusting the seat height, information regarding the 'desk recommendation height,' 'monitor height,' and 'reachable shelf height while sitting' is visualized. This will prevent visual clutter and information overload.

System Implementation
The prototype (Figure 6) was built in Unity with SteamVR, an HTC Vive HMD and tracking system to create an immersive experience. We decorated the virtual environment to look like a room (Figure 1) and added the parametric desk. A 'store' with objects to be used as props, such as laptops, monitor of various sizes, and books is located behind the user.

A Microsoft Kinect for Windows tracked the users' joint positions. The joints were used for ergonomic measurements, as input in conjunction with voice commands, and for animating the first and third-person avatars. The Kinect was calibrated to the floor, and the Vive was calibrated to the Kinect using an affine transformation matrix calculated with OpenCV. Based on prior experience with speech recognition for non-native speakers, we used Wizard of Oz for voice commands.

Prior to a design session, we 3D scanned the user with a Kinect v1 and Skanect [32] and we recorded joint positions with the Kinect v2 as shown in Figure 7. Both model and joints were used in Maya to rig a posable virtual avatar. A toon shader is applied to make avatars less creepy.

We attached a Vive tracker to the palms of both hands to accurately track orientation and position. Two microswitches were added to create a simple pinch-glove. One of them is for grabbing and moving virtual objects (pinch gesture), the other is for resizing the virtual desk. When resizing, the hand is held parallel to the orientation of the plane that needs to be moved, as shown in Figure 5. Using the orientation allows for ambiguous voice commands such as *"until here"*. Objects collide in a rigid body simulation and can be stacked or positioned on the tabletop and shelves. We attached the third tracker to the chair and made a matching virtual model. In the virtual environment, users can find the chair and easily adjust the height.

USER EVALUATION
We conducted a small user study and let six participants design with Body2Desk. The study aimed to explore how people design a personal desk with interactive guidelines (*How do they trust, and use the guidelines? How guidelines affect design process?*). Therefore, we analyzed their design process, then we fabricated their design. We let them use it for four hours to see how their virtual design related to real comfort.

Participants
We recruited six participants (mean age=27, 3 female) through an online community board used by university students. The height of the tallest participant was about 180cm and that of the shortest participant was 151cm. Therefore, it was possible to see how the guidelines are applied to the different size of people. The participants had no experience in industrial design or ergonomics and used their desks for more than three hours per day. Half of the participants (P1, P2, and P5) worked mostly at home, while the others worked in their labs. All of the participants had unique needs and requirements for their desks.

Procedure
The study consists of four stages: *sensitizing*, *designing*, *making*, and *using* (Figure 8). The goal of the first stage was

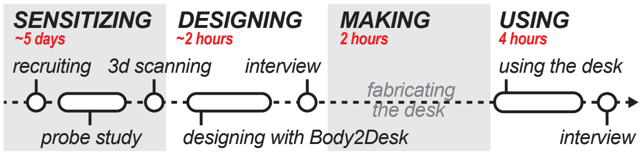

Figure 8. The research process consisted of four stages.

to sensitize the participants and let them think about their needs before the design session. We provided probe packages with worksheets that asked participants to show their frequent working postures, likes/dislikes of their current desk, photos of objects on their desk, and a floor plan of the room. We also 3D scanned each participant's body to create their virtual avatars, and personalized the VR environment for the participant to make it look like their workspace.

In the *design* stage, we introduced the Body2Desk interface briefly. After 10-minute practice, the participants started designing with the system until they were satisfied with their desk result. We employed a think aloud protocol and captured their design activity from three different perspectives: two from virtual cameras (the participant view and the third-person view), and one from the real camera (capturing the participant from a side view). The design session was followed by a semi-structured interview regarding their design process and rationales.

We provided transportation so each participant could bring their PC, monitor(s), peripherals, and other objects they needed for their work. In the *making* stage we gave participants a break in which we quickly fabricated their design in an empty office room. We exported parameters from the Body2Desk prototype and configured an aluminum T-Slot frame, shown in Figure 10. We fabricated the desk from 16mm honeycomb cardboard and installed their personal items.

In the *using* stage and after their break, we let participants work on the fabricated desk for a minimum of four hours, doing usual activities without any interference, and gave them access and keys to the room. This stage was conducted on the same day as the *design* stage, as we wanted the participants to reflect on their design process while using the desk. The session concluded with a short interview to sample the participants' experience using their own design and any differences between their virtual and real-life design assessment.

For the analysis, we transcribed design behaviors and narrations from the interview recordings. We used open coding and axial coding methods to identify how the participants interacted with guidelines, and how they utilized them throughout the design process. Additionally, we compared the dimensions between their designs and their existing office desk.

RESULTS

All of the participants designed a desk that met their personal needs and preferences, resulting in six unique designs, shown in Figure 10. For example, P3 (Figure 9,left) designed a half-width shelf design to fit their vertical monitor and to meet both recommended monitor height and reachable shelf height while

Figure 9. (left) P3's height is 172cm, and he uses 27 inch vertical monitor. (right) P5's height is 158cm, and and she uses 25 inch horizontal monitor and laptop. These leads to different fitting designs as shown here.

sitting. P6 repurposed the footrest as a secondary shelf below the tabletop, and P2 made three shelf widths, all different, and tried a creative layout for aesthetics.

All designs met the ergonomic recommendations of the guidelines. Four of six participants made the tabletop higher than their current one (average 5.4cm) to make it fit the recommended range. Five participants dramatically increased the height of their monitor by 18cm on average. P3 also mentioned that he raised his monitor (15cm) when he went back to his office after the experiment. These results indicate that the system makes users aware of ergonomics and lets them effectively apply guidelines in their designs.

Body2Desk engaged participants in an iterative design process that took 40 minutes on average. All participants revisited and adjusted parameters, and the interactive guidelines were used throughout the design process. All six participants started with adjusting their seat and tabletop height accordingly, following the recommendations. The remainder of the design process varied among the participants. P2 and P4's primary concern was to avoid back pain as they spend many hours at their desks, so they relied on the pose feedback. On the other hand, reachability and comfort were the driving design factors for others, such as for P6. All participants used the guidelines as a final evaluation check.

All six participants quickly mastered the Body2Desk interface, except P2 who required more time. All of the participants freely acted out scenarios of use, walked around to look at their desk from various perspectives, and occasionally switched from standing to sitting positions. They tried out different techniques to evaluate usability, comfort, and good posture: using their bodies, virtual avatars, virtual objects, and referring to the guidelines. Hands, feet, heels, and elbows were commonly referenced body parts to set parameters. Participants often set the initial parameter using a voice command and gesture but used the buttons for minor (re-) adjustments.

We observed users design with their bodies in two ways. Similar to experience prototyping [6], they acted out work activities and frequently used props to understand their needs. Participants also used their bodies as a tool to test reachability. P3 remarked that *"With the virtual body figure, I could test if I could grab things in the left corner."* P1 implied that whereas the guidelines provided health-related information, comfort could be tested with his body by simulating several activities.

Figure 10. The research process consisted of four phases: sensitizing, designing, making, and using. We started with a probe study and prepared the personalized prototype. Then, participants designed a desk, and used it after we fabricated their design result.

Interaction with the Guidelines

Desk and monitor height recommendations guided early-stage design decisions. An initial setting based on the recommendations was typically followed by occasional minor adjustments for comfort. For example, P1 set the desk height first but later lowered it after he simulated typing. P2 first positioned the monitor in the middle of the recommended range but moved it a little bit higher because he preferred a high monitor.

All of the participants needed some time to gain confidence with the guidelines and to confirm that those were generated from their personal body measurements. Most of them confirmed the reachability guidelines by trying it out, and this process built trust between the user and guidelines.

Whereas the tabletop and monitor recommendations were strictly followed and related dimensions were set first, participants followed other guidelines more freely. Guidelines such as shelf reachability and workspace motion envelope depend on personal preference and use. For instance, although P2 checked the reachable depth range, he set the tabletop depth deeper beyond the reachable line for storage space. Similarly, the workspace guideline also indirectly helped users arrange their objects. For example, P2 mentioned, *"I used the primary zone for papers, and used the secondary zone for the keyboard. I don't use keyboard often, but it should be in my reachable range."* P6, however, stated that it was not useful as she arranges objects based on her habits.

The recommendation that dealt with space around and behind the desk was not used (Figure 3, bottom right). P4 indicated that these guidelines were only useful if she was allowed to rearrange her other furniture. Other participants mentioned they needed more information. P3 asked to *"turn on"* the monitor to estimate an appropriate distance, which could be a new guideline. P4 and P6 suggested guidelines on aesthetics such as for distribution or alignment of surfaces and objects.

In reflection, participants mentioned that context-aware feed-forward interactions made the guidelines available when they needed them and were not a distraction. Only P6 said she would have liked to hide the guidelines after setting the tabletop height.

Evaluating Good Posture during the Design

When the participants designed their desks in a first-person perspective, they evaluated several usage scenarios and used and moved virtual objects to help them. They did not only design the desk as an object in space but as an object that they use in their routines. P6 stated, *"the first-person view was very comfortable because I felt like I was using this desk. I was engaged in the scenario."*

The small virtual avatar was referenced frequently. All participants grabbed, moved, and rotated the Mini-me to check their real-time posture while posing and simulating. Five participants out of six intermittently looked at the Mini-me to check the posture feedback. P2 mentioned, *"I usually sit correctly but I wanted to be convinced that I sat in a proper way while designing."* P3 and P6 used Mini-me to evaluate their posture from a third-person perspective and the immediate feedback helped them to make rapid iterations. Additionally, the Mini-me was helpful to visualize the footrest while sitting on the chair. P5, while looking at the Mini-me, moved his feet up and down to estimate the proper height and depth for the footrest.

The interaction with Freeze-me was appreciated in the later stages, when participants evaluated their designs and checked whether they satisfied the recommendations. Four people froze their design to check their pose just before finalizing their design. P2 and P6 stated, *"In the last moment, I froze my usual posture and check if the desk design fits my body. Mini-me kept moving with me, so it was hard to focus on one posture."* Participants also valued Freeze-me because it was larger than the Mini-me and provided more detail. P1 and

P3 also mentioned, *"The freezing function was particularly helpful when I wanted to see on a large scale. Regarding the footrest, I needed to accurately check if the footrest was located on my heel position, not on the ankle."* Additionally, P6 used the freezing function to check the particular posture that blocks her sight, for example: the act of taking a nap on her desk. When they activated the freezing function, participants tried various angles and positions by walking around their frozen bodies or sitting down and standing up.

In some cases, participants combined different perspectives simultaneously. Whereas participants adjusted parameters in a first-person perspective, occasionally they posed, froze their bodies, and adjusted parameters to their Freeze-me from a third-person perspective (e.g. after capturing a typing pose, they set the height that fit the fixed body's elbow position).

Reflections After Using the Desk

After using their personalized desk for four hours, participants could reflect on design and use. All six participants indicated satisfaction with their design, and four of them wanted to bring the desk to their homes. In the post-interview, they mentioned two key reasons. First, scenarios they prototyped in VR, felt very similar in reality, as their designs fit their body and the objects they use. Second, the parameters they set based on the guidelines provided more comfort than they expected from the VR environment. P6 indicated that, *"The monitor height from my design was higher than the one in my office, but it was more comfortable and reduced my neck pain."*

However, using the desk, participants found several problems that they didn't realize while designing. The materiality of the physical desk provided haptic feedback and let them experience support. For instance, P4 indicated that she had trouble setting the footrest with her feet floating in the air. Some participants re-evaluated trade-offs after using their desks. P2 and P4 wanted both a deep desk and reachable shelves; therefore they compromised on aesthetics and increased the depth of their shelves. After using the desk, they found that they could decrease the desk depth about 10 cm (and shelves accordingly) as the shelves looked too large. P5 lowered her monitor by a few centimeters because she couldn't evaluate the text size in VR (still within the recommended range).

Some participants realized they forgot to consider some usage scenarios in the VR design session. In the interview, P6 remarked that she enjoyed typing while putting her entire arm on the tabletop, but she did not test that action in VR. For other participants, using shelves (P2, P3) or a footrest (P6) was new. After using them in real life, they had more ideas on how to design them, and how to use them in the future.

DISCUSSION AND FUTURE WORK

We personalized human factor guidelines, applied them in a design system, and evaluated their use with users. The prototype posed several limitations; for instance, wrist angle could not be measured and the study was preliminary with a few participants. Nevertheless, the results indicate that the system makes users aware of their pose and lets them design a desk that meets human factor guidelines. Here, we discuss our insights and implications and challenges for future work.

Interactive personal guidelines let participants fluidly switch between being *"user"* and *"designer"* as they carefully design a desk that fits their needs. The guidelines took on the role of an expert and helped them become more aware of their comfort and health, in addition to providing professional advice. The participants trusted the interactive guidelines after informal verification with their bodies. To make sure that the design is within the recommendations, a future system could support a pre-flight check. This will help users gain a final confirmation. Additionally, future system can support earlier stage of design by automatically generating recommended configurations based on the user's initial exploration.

Future research should look into how to present conflicting recommendations, such as for reachability. Other guidelines depend on the task, such as typing or crafting. As future systems might include a more complicated set of guidelines, we need to further study interrelationships between them. Systems could prioritize certain guidelines based on importance or frequency of use, give freedom to users by mapping the conflicts, or hide guidelines that are not used.

Participants frequently used Freeze-me to evaluate their static poses in relation to their desk from a third-person view, and made changes to the desk dimensions. However, the Freeze-me did not react to design changes, so the users needed to freeze their bodies repeatedly to test resulting poses. Providing a virtual avatar with agency [4] could be a possible next step, such as making the avatar responsive to changes in the design or to playback usage scenarios.

Body2Desk could be work with Augmented Reality (AR) with the benefit of including the real contexts of the users. In the future, it could also be part the daily working environment in which posture is continuously monitored and thus fully merge use and design. On the other hand, tablet-based systems require different interactions, as they do not support embodied actions. Therefore, we can provide agency with body figures for simulations or support multi-user interactions to assess the pose and workplace of another user.

Recommendation techniques we investigated in this research can also be applied in other domains that benefit from ergonomics and personal use, such as home kitchens, car interiors, or interior layouts. Using our system augment the role of experts in the future by providing personal guidelines.

With the advent of digital fabrication and flexible manufacturing, we need to investigate interactive design systems that support tailoring designs for a unique person rather than for a population. In this paper, we made a first step toward including human factor guidelines in personal design tools. In the future, augmented and situated guidelines will not only enhance the designing of objects, but can also be part of daily life and active posture measurement.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT & Future Planning(NRF-2015R1C1A1A01051808)

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