WRLKit: Computational Design of Personalized Wearable Robotic Limbs

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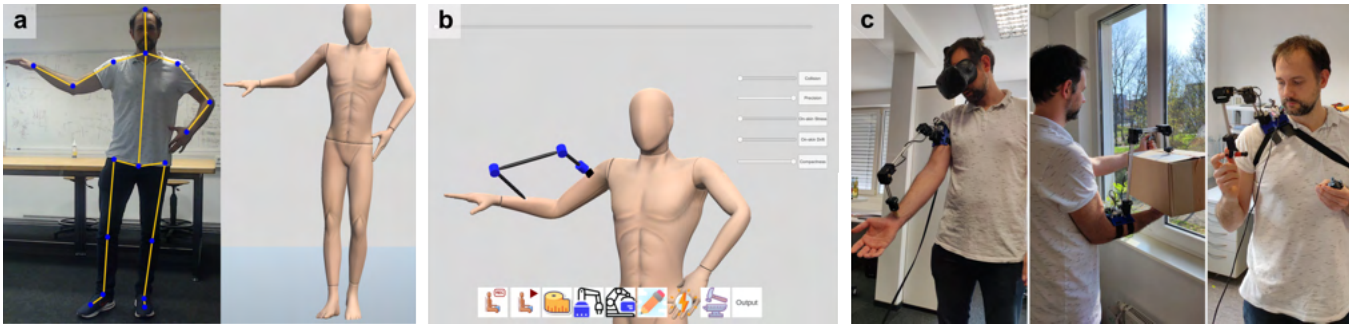

Figure 1: WRLKit Enables rapid prototyping of personalized Wearable Robotic Limbs for robotics novices. Users demonstrate tasks in front of a camera (a), specify the mounting location and reach targets (b), and export design files for digital fabrication for diverse applications (c).

ABSTRACT

Wearable robotic limbs (WRLs) augment human capabilities through robotic structures that attach to the user's body. While WRLs are intensely researched and various device designs have been presented, it remains difficult for non-roboticists to engage with this exciting field. We aim to empower interaction designers and application domain experts to explore novel designs and applications by rapidly prototyping personalized WRLs that are customized for different tasks, different body locations, or different users. In this paper, we

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present WRLKit, an interactive computational design approach that enables designers to rapidly prototype a personalized WRL without requiring extensive robotics and ergonomics expertise. The body-aware optimization approach starts by capturing the user's body dimensions and dynamic body poses. Then, an optimized fabricable structure of the WRL is generated for a desired mounting location and workspace of the WRL, to fit the user's body and intended task. The results of a user study and several implemented prototypes demonstrate the practical feasibility and versatility of WRLKit.

KEYWORDS

Wearable robotics; supernumerary robotic limb (SRL); computational design; design tools; rapid prototyping; fabrication.

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1 INTRODUCTION

Wearable Robotic Limbs (WRLs) augment human capabilities by means of robotic structures mounted on the body. WRLs synergistically work on and with the body, forming a kinematic chain consisting of human body movement and robotic actuation that assists users in diverse contexts, from personal to professional purposes. Examples include a wide spectrum of functionalities, ranging from hand augmentation [16, 20, 42] and balancing the body [39, 41] to augmenting reachability [51, 53] and hand-shaped interfaces [60].

Pioneering research on WRLs has primarily focused on investigating devices that each are targeted for a specific use case [5, 43] and a specific location on the body [45, 51, 54]. This has established significant foundational knowledge regarding device designs, robot engineering and techniques for robotic control, all primarily targeting expert roboticists. However, it remains difficult for non-roboticists, such as interaction designers or application domain experts, to explore new designs and new applications of WRLs. Prototyping custom WRLs is an inherently iterative task, consisting of repetitive cycles of ideation, fabrication and evaluation, which are complex and time-consuming with existing solutions. Compared to classical robots, designing WRLs further introduces many challenges related to the human body, such as individual body dimensions of users, dynamic body movements, and comfort while wearing. Our work seeks a new approach that will empower the broad group of creative professionals to engage with this exciting new field by easily and rapidly designing and prototyping their own functional solutions.

The primary contribution of this paper lies in demonstrating the feasibility of body-centered computational methods in rapid prototyping of WRLs. This is the first work that uses postures, captured while executing a task, for the generation of versatile and customized WRLs. As a proof of concept, we present WRLKit, an interactive body-aware computational design approach that enables users to rapidly prototype a customized WRL, without needing substantial robotics expertise (see Figure 1). By combining camera-based capture of the user and an interactive graphical design tool, it optimizes the overall structure of the WRL to fit the user's body and intended task and produces a specification for the digital fabrication of the personalized WRL. WRLKit is informed by a set of design considerations for WRLs that we have derived from the literature on wearable computing and robotics.

WRLKit's key unique properties are to a) capture a user's individual body dimensions and range of motion from demonstration, b) model the sequence of body poses that a user assumes in a task and ensure the generated WRL is compatible with them, c) flexibly support various mounting locations on the body, d) support flexibly defined workspaces on the body surface and in the user's peripersonal space, and e) optimize for wearability criteria (minimizing on-skin stress, drift, device size and collisions).

To this end, we propose the following design process: The user first demonstrates the intended task. Using a standard RGB camera and a markerless Motion Capture (MoCap) system, WRLKit captures a personalized skeleton model and a sequence of body poses the user has assumed while performing the task. This data is fed into a 3D body model that is visualized in the interactive graphical design tool. Here, the user can decide on the placement of the WRL on the body and define what locations the WRL should be able to reach, on the user's body surface or in peripersonal space. Based on these specifications, WRLKit then automatically generates an optimized WRL structure, modeled as a max. 3DOF articulated robotic manipulators, consisting of serially connected rotary actuators. It maximizes wearability while optimizing for the WRL to be able to reach the desired locations despite the natural changes in the user's poses that have been demonstrated. The user can inspect the proposed design and adjust parameters as needed until satisfied with the design. WRLKit then exports models of the personalized WRL that can be fabricated using 3D printing and laser cutting. The modular design can be easily assembled with off-the-shelf servo motors and connected to a standard microcontroller.

To demonstrate the feasibility and versatility of WRLKit, we used it to design and fabricate examples of WRL prototypes, mounted on the arm, shoulder and hip, for applications in haptics, personalized assistance with holding objects, and performing tasks while hands are busy. Results from a user study offer further insights and lessons learnt. We conclude by discussing limitations and future work.

In summary the main contributions of this paper are:

- Demonstrating the feasibility of body-centric computational methods for rapid prototyping of WRLs, using natural body postures captured while executing the real-world task.
- A set of design considerations for customized WRLs based on literature from wearable computing and robotics.
- WRLKit, an interactive body-aware computational design approach for WRL and a proof-of-concept implementation thereof.
- Validating the practical feasibility of WRLKit with a set of example applications and through a user study.

2 RELATED WORK

This work is informed by prior work on wearable robotics and interactive design and fabrication methods:

Wearable Robotics. Wearable robotics has become a vibrant field of research in the past years. Several main types of wearable robots can be distinguished: (i) wearable robotic limbs (WRLs), often called supernumerary limbs, assist the user by providing additional limb-like robotic structures [58], (ii) prosthetic limbs replace missing body parts [18], (iii) exoskeletons help in enhancing the physical performance of the user's existing limbs [59], and (iv) moving robots roam on the user's body to perform various tasks [7]. Our work contributes to the first type. WRLs are vastly studied and different structures are proposed for wearing at different body locations and for various functionalities. For instance, prior work has explored a shoulder-mounted extra arm for above-the-head work [29], dexterous torso-mounted robotic arms [45], a forearm-mounted WRL [52], or additional finger-like structures for structural support and synergistic interactions [25]. The literature features diverse WRL end-effectors, some with a camera [19].

Typically, solutions focus on one specific form factor with a fixed mounting location. Comparably little work has investigated a more versatile structure. A very flexible snake-shaped wearable robot with 25 degrees of freedom has been designed for very versatile use on the body in diverse geometric configurations [1]. Other work presented a physical modular toolkit that allows the user to build a customized WRL by assembling servomotor and sensor units [24]. Recent work has also shown that the same hand-shaped interface can be effectively mounted on different parts of the user body as well as the environment [60].

Researchers also have explored the interactions between the WRL and the human user for controlling the WRL's motion and trajectory [37]. This is a demanding space because the user's body is often busy when operating a WRL, which renders classical touch or gesture-based interaction useless and calls for novel interactions that are compatible with the primary task. One stream of research focuses on robot planning to detect the user's activity and automatically control the robot so that it synergistically integrates with the user's task, without any need for explicit interaction [30]. This direction has been investigated, for instance, for automatic balance assistance and load reduction [40] or for assistance with manual construction tasks [30]. A complementary stream of research is investigating how the user can control the robot through explicit interactions. For instance, prior work has shown that remapping a user's foot movement to robotic arms can be a powerful strategy [44]. Other options involve controlling a WRL with the user's pinky finger [28], with the back of the hand [23], or using EMG-captured muscle movement [31].

The embodiment of WRLs in virtual reality is studied in [3]. WRLs also present rich opportunities for haptic interfaces. For instance, HapticSnakes present waist-worn robots that can deliver multiple types of feedback on various body locations [2] and Haptic PIVOT is a wrist-worn haptic device that renders virtual objects into the user's hand on demand [22]. However, prior work has mainly focused on proposing novel WRLs structures targeted for a specific task or location of wearing, rather than providing design assistance for prototyping personalized WRLs. WRLKit helps the designer with reducing the iterative cycles of fabrication-evaluation in the prototyping process, by providing design assistance.

Interactive Design and Fabrication Tools. With the rise of digital fabrication methods, research has also investigated interactive design and manufacturing methods. A stream of computational design approaches offer functional abstraction. Instead of manually producing a design, the designer can specify high-level functional goals in an interactive design tool. Built-in forward models and optimization would then create a functional design either fully automatically or with the designer-in-the-loop. This powerful principle has been explored in a variety of fields, from material science for building structures with specific physical characteristics [11] such as softness [21], to designing functional mechanisms [4, 10], passive orthoses [56] or creating body-worn sensors that are personalized for a user's personal anatomy [38].

The computational design of customized robots has also been investigated, for instance for embedding robotic actuators in 3D objects [26] or actuating everyday objects [27], or for optimizing a robotic device based on a high-level motion specification [13]. [33] proposed an interactive design system that automates the design process of robots while offers customization for morphology, proportions, gait and motion style. Molecubes offers an assembly-based design tool for low-cost modular robotics with a graphical interface to simulate and control them [61]. Commonly these design tools use a graphical interfaces; some are also based on capturing a user demonstration [27], which inspired our capturing phase. To our knowledge, no computational design method exists for WRLs yet. We prioritized hardware structure fabrication over motion planning and real-time control of customized WRLs in this work.

3 DESIGN CONSIDERATIONS FOR WEARABLE ROBOTIC LIMBS

Wearable Robotic Limbs (WRLs) perform tasks directly on the body or in the user's peripersonal space. This presents a hybrid set of challenges, different from conventional robotics and wearable technologies, that need to be addressed to design a useful extension of the body. The identification of design considerations for WRLs was an iterative process consulting relevant literature on wearables [12, 36, 46, 57] and robotics [8, 49, 55]. By critically reviewing and synthesizing the important design parameters from these two domains, we derived a set of considerations that concern the design of (1) wearable and (2) robotic structures.

3.1 Wearables Design Considerations

From the wearability literature, we extracted four key considerations that played a crucial role in shaping the design of our WRLs:

Individual Body Characteristics. Designing wearables poses a challenge due to the variability in sizes. [12]. Each person's body is unique. Body size and shape, including the length of limbs, can vary significantly between individuals. These differences can affect the fit and function of a WRL and should therefore be taken into consideration for the computational design. As manual measurements are time-consuming and error-prone, these characteristics should ideally be automatically captured.

Dynamic Body Pose & Motion. Human motions can be considered as a constraint as well as a resource in the design of wearable devices [12]. Individual body characteristics may not only affect

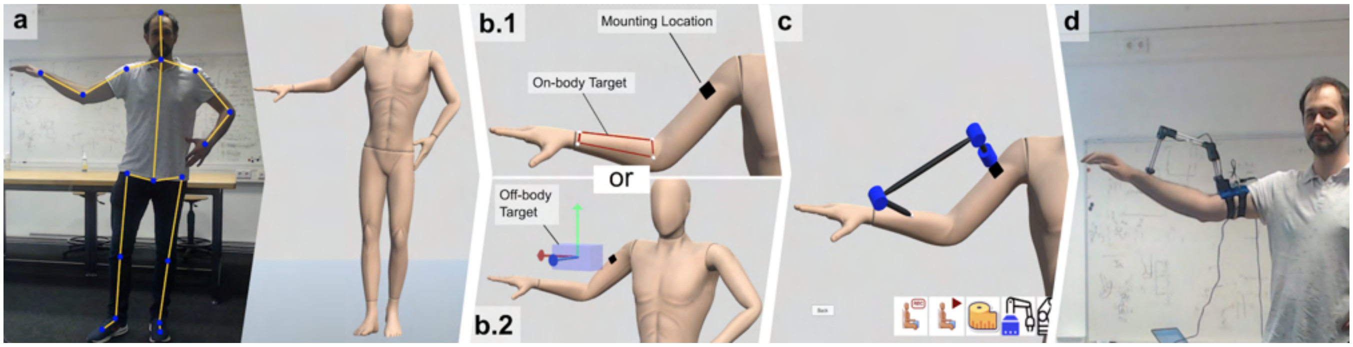

Figure 2: After markerless capture of body poses for the task with a camera (a), users specify the mounting location and the target of the WRL which can either be on-body (b.1) or off-body (b.2). WRLKit then uses the recorded poses and specifications to generate and visualize an optimized WRL structure (c). When the user is satisfied, fabrication-ready files can be exported for digital fabrication and rapid assembly of the functional prototype (d).

the robot's size and attachment, but also its required range of motion. It must be designed to move with the user's natural range of motion to ensure it does not restrict movement or cause discomfort. Moreover, the body pose may be changing during task execution, depending both, on the task and on the user's personal motion patterns. Hence, another challenge is to personalize for a user's individual motion patterns during task execution. In addition, body motion and posture may be considered to be a constraint, as the human body could collide with the WRL while performing a task.

Attachment at Different Body Locations. Identifying an unobtrusive placement of a wearable is a crucial part of the design process [12]. The human body offers many different locations for attaching a WRL. Each has unique properties, not only in terms of the robot's workspace on the user's body and in the peripersonal space, but also regarding its compatibility with everyday movement. Body locations also offer critical affordances for tasks of different granularity: Mounted on the hip, the WRL affords large-range actions at a fixed location in the world, as it benefits from the relative stability of the torso, which is typically moving considerably less than human arms and can sustain more heavy weights.

In contrast, going further down the kinematic chain and mounting the robot on the user's lower arm or on the wrist, may offer superior performance for dexterous manipulation tasks on handheld objects. Therefore, a computational design approach should allow the designer to flexibly choose an attachment location and inspect its consequences on the robot's structure and workspace.

Wearability. The WRL must be comfortable and easy to wear for long periods of time. Comfort can be considered as a response to the environment [46]. Therefore, the device should be compact, reduce stress on the user's skin as well as be designed with the user's body in mind [12]. A computational design approach must therefore aim to minimise the causes of discomfort, e.g. the stresses and drifts at the attached body location.

3.2 Robotics Design Considerations

From the WRL literature, we identified two additional considerations that were crucial in constructing our design decisions set:

Reachability on the Body and in Peripersonal Space. To build up a representation of the robot's workspace, the 3D work envelope area of the robot is filled with reachability data describing the capabilities of the corresponding kinematic chain in reaching at a sepecific point [8, 49]. While the reachability of a stationary robotic arm is clearly defined, dynamic poses and motion patterns of the body itself pose a major challenge for the design of WRLs. In addition, different tasks also require different ranges of motion and reach. For example, a person needing to hold an object on the body may require a different range of motion than a person needing to lift a heavy object from the ground. Moreover, a WRL might operate either directly on the body or in the peripersonal space. This dynamic variability in body pose, motion and robotic workspace needs to be considered to ensure that a target can always be reached while avoiding collision with the body.

Safety. Safety is a fundamental challenge in any approach that involves human-robot collaboration (see e.g. [15, 55]). Designers must consider various safety aspects throughout the design and development process. The mechanical hardware of the WRL should be designed to minimize its potential to harm the user. A computational design approach must therefore select motors that are not overly strong and design the WRL's structure to minimize potential collisions with parts of the body during movement. Furthermore, safety needs to be ensured during real time control of the robot's movement, using sensor information to dynamically avoid collisions with the body and to ensure that forces applied on the body are within a safe range.

4 DESIGN PROCESS

To address these design considerations, we propose WRLKit, a body-aware computational design and fabrication approach that enables users without specialized robotics expertise to quickly prototype personalized WRLs. This section presents WRLKit and gives an overview of the steps involved in the process of designing a customized WRL. Although the person who designs a WRL using WRLKit may be different from the end user who uses the WRL, we refer to both simply as *users* in the following.

4.1 Capture Body Dimensions and Motion Patterns

Designing a WRL that is effective and comfortable to use does not only require information about the user's body dimensions (i.e., body height and length of limbs) but also on the dynamic body poses and motion patterns that a user naturally performs while executing a task. Measuring and entering this information manually would be prohibitively complex. Therefore, we propose to capture the user's body and movements while the user is demonstrating the real-world task that the WRL will be designed for, and harness the recorded information for computational optimization.

First, the user performs a Motion Capture (MoCap) with a commodity RGB camera (see Figure 2a left). To that end, we use the VNect library [34, 35] for markerless real-time pose estimation. It combines a pose regressor based on a convolutional neural network with a kinematic skeleton fitting, providing the user's 3D joint positions in real-time. WRLKit records the time sequence of 3D joint positions and parameterizes a biomechanical human model based on Unity to the user's body size and proportions. It visualizes the recorded motion sequence with a humanoid avatar in the graphical design tool (see Figure 2a right) implemented using Unity [47]. The user can re-record and playback the motion capture at any time.

4.2 Specify Design Parameters

Next, the user specifies the desired properties of the WRL in the graphical design tool at a high functional level of abstraction:

Specify Mounting Location. The user's body part where the WRL is attached directly influences, for instance, the target range of the WRL, the dexterity of the user in working with the WRL, the probability of potential collisions with the user's body, and the comfort of wearing. Therefore, it is important to choose a mounting location on the user's body that best fits the intended task.

WRLKit offers to specify the mounting location of the WRL by clicking on the surface of the humanoid avatar in the design tool (see Figure 2b.1). A tentative WRL design is immediately visualized. At any time, the user can change the mounting location by clicking on a different segment on the humanoid avatar.

Specify Targets. We define the targets as the set of spatial points that the WRL's end-effector should reach. These points are defined respective to the body.

The target can either be defined as an *on-body* area on the surface of the user's body (e.g., to provide haptic feedback), or as an *off-body* 3D volume in peripersonal space (e.g., to hold an object in the user's proximity).

The user can use WRLKit to specify the targets with respect to the user's body as follows: (1) On-body targets are defined by selecting a quadrilateral convex area on the surface of the humanoid avatar (see Figure 2b.1). The user selects this area by placing 4 points on the humanoid avatar in the tool specifying a trapezium, a quadrilateral whose sides are not necessarily parallel.

(2) Off-body targets in peripersonal space are defined by a cubic volume in the proximity of the human model's body (see Figure 2b.2). Users can scale or move the cube to the point of interest in the vicinity of the human model's body. The cube's position and orientation are defined in the body-centric coordinate system relative to the position of the mounting location.

4.3 Optimize the WRL Structure

WRLKit then generates a parametric WRL with a 3DoF articulated robotic manipulator structure, and optimizes the respective link lengths (see Figure 2c).

There are many objectives that contribute to the wearability and functionality of a WRL.

WRLKit optimizes the following objectives:

Maximize Compactness. A compact WRL is important for comfort, aesthetics, and safety. We define compactness as the volume of the WRL workspace, which is the set of spatial points that the WRL structure can reach. A more compact WRL can be more easily worn on the body and tends to interfere less with everyday body movement, but has a more restricted workspace.

Minimize On-Skin Stress. The stress caused by the torques and forces exerted on the body at the WRL's mounting location can reduce the comfort of wearing and therefore should be minimized.

Reduce Drift. Torques and forces coming from the WRL can also cause the mounting unit to drift on the user's body. We postulate that this is due to torques and forces exceeding the static friction between the skin and the base unit at certain configurations. To reduce drift, we minimize the peak values of torques and forces across all configurations.

Reduce Collisions. Avoiding collisions between the WRL and body parts is an important criterion for ensuring safety and wearability, as some WRL structures may not be wearable if collisions with the user cannot be avoided.

Maximize Reachability. The end-effector of the WRL should be able to reach the defined on-body or off-body targets.

Depending on the specific requirements, the user can fine-tune the optimization criteria by giving greater or smaller weights to individual objectives. For example, users may prefer a more compact WRL structure with somewhat increased on-skin stress for a more wearable and portable WRL, or maximize reachability at the cost of a larger structure. In addition, the user can specify the length and weight of an end-effector for WRLKit to consider during optimization.

In our prototypical implementation on a standard CPU (Intel(R) Core(TM) i7-6700K CPU @ 4 GHz), this optimization process takes approx. 11 seconds for a 10 seconds recording (30 Hz) of the user demonstrating the task (in future versions, performance could be further increased with a GPU).

We detail the optimization for generating WRLs in Section 5.

4.4 Inspect and Iterate

The generated WRL structure is directly visualized in a 3D view of the body model (see Figure 2c). The user can then inspect the WRL's configuration for the captured body poses.

The tool visualizes a representative set of the target points from the workspace of the WRL and human model's combined kinematic chain with green dots in the 3D view and does so for all of the captured body poses at once. We refer to this set of points as human-WRL target points. This provides a representative overview of the possible end-effector locations during the recorded task sequence. Users can click on any of them to see the corresponding body pose together with the configuration of the WRL visualized in the 3D view. This allows the user to evaluate the structure and identify possible issues with the WRL's size, placement, aesthetics, reachability, or potential collisions with the user's body.

At any point, the user can revise any of the previous design decisions and, if desired, re-generate the WRL structure.

4.5 Generate Fabricables

When the user is satisfied with the design, WRLKit automatically generates fabrication (STL, DXF) and design (IPT) files

for non-technical users to fabricate components for the final WRL (see Figure 2d). We utilized Autodesk Inventor Professional software for designing the robotic structure.

We opted for a classic 3DoF articulated robotic manipulator structure with the serially connected off-the-shelf rotary actuator, as this is versatile and easy to fabricate. Its modular structure, consisting of motor connection hubs, links, a base unit and an optional end-effector, makes it easy to assemble. Moreover, parts can be reused when iteratively creating a prototype.

To further foster modularity, the fabrication files are generated separately for the following parts of the WRL (see Figure 3):

Links. Our current prototype uses lasercut acrylic sheets for links due to their sturdiness, cost-effectiveness, manufacturing speed and ease of assembly. The lengths of the links are updated according to the output of the toolbox. If no laser cutter is available or the link's length exceeds those supported by the cutting device, links can alternatively be cut from aluminum rods. The required lengths of the rods for each link is indicated in an exported text file.

Motor Connection Hubs. For this work, we used Dynamixel XC430, XL430 and XL330 servomotors for their ease of use and attainability. The motor connection hubs are designed to be manufactured with 3D printing since they need to be exactly tailored to the motor (Dynamixel XL/C 430) geometry. However, these only need to be fabricated once and can remain assembled together with the motor if the motor is going to be reused in a different WRL. We offer design files for the motor connection hub that fits to laser cut links of aluminum rods. Users can modify 3D-printed connection hubs to fit different actuators of their desire.

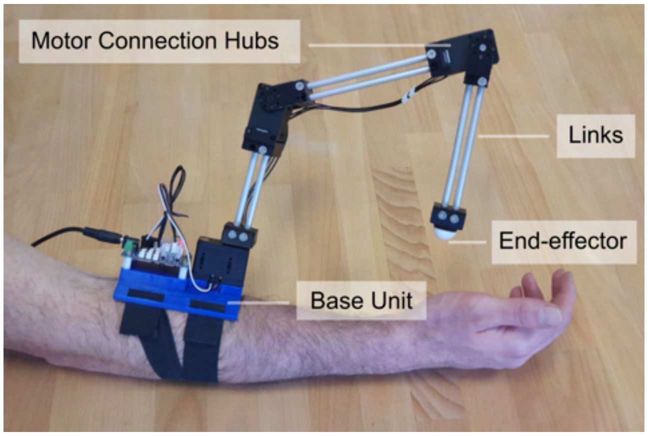

Figure 3: A closeup of a WRL structure showing the base unit, links, motor connections hubs, and a hemispherical end-effector.

Base Unit. The base unit is designed as a hollow cylindrical sector to conform to surface curvature of the body parts. We use two straps to wrap around the body for a tight fit. To further improve the fit to the body, users can adjust the radius of the curved base plate by either choosing among a set of pre-defined curvatures (small, medium, large) or precisely altering the curvature themselves.

End-Effector. WRLKit offers a set of simple end-effectors with pre-set weight and sizes (see Figure 4). Currently these comprise a universal fastener, a bistable gripper, a flexible hemisphere, and 4-legged soft supporter. In addition, users can extend the set of end-effectors depending on their requirements.

Assembly. The assembly of the WRL structure is done by connecting the motors and links through the motor connection hubs. The 3D-printed hubs accommodate screws and nuts to fasten the motors and links in the structure. The shafts of the motors used in the project readily come with threaded holes. In contrast, the rods are stabilized through nuts and screws, without relying on any threading in the 3D structures, drastically improving the lifetime of the structure. The motors used in the project can be controlled using any controller and driver combination capable of half-duplex UART or TTL communication and providing 12 V.

5 OPTIMIZATION

In this section, we detail the optimization process to generate a personalized Wearable Robotic Limb (WRL).

5.1 Problem Definition

We define a WRL as $\mathcal{W} = \{L, J\}$, where $L = \{l_1, l_2, \ldots, l_N\}$ and $J = \{j_1, j_2, \ldots, j_N\}$ represent the set of link lengths and joints, respectively. WRLKit then solves a multi-objective optimization routine for the optimal link lengths, L, for a given task.

Optimizing the link lengths of a WRL is an important aspect of designing WRLs with better wearability because it also influences the functionality of the WRL. The link lengths determine the

Figure 4: A set of end-effectors: universal fastener, bistable gripper, flexible hemisphere, and 4-legged soft supporter.

workspace and the target points that the kinematic chain of the user and WRL can reach, consequently affecting the dexterity of the user wearing the WRL. By optimizing the link lengths, WRLKit ensures that the WRL structure is capable of reaching target points with the desired level of accuracy. The multi-objective optimization also ensures to reduce on-skin stress, the probability of drift at the mounting location, collisions between the WRL and user's body parts and the WRL's compactness (i.e., its size and weight). Compactness does not only enhance wearability but also can reduce power consumption, as the actuation of a lighter WRL consumes less energy–an important point for a wearable robot.

To find the optimal link lengths, we solve a multi-objective optimization problem designed to address the criteria (1) on-skin stress, O_s, (2) on-skin drift, O_d, (3) compactness, O_{cp}, (4) reduced collisions with the user's body, O_{cl}. The overall objective function is defined as:

$$\begin{gathered}\arg\min_{l \in L} \lambda_s O_s + \lambda_d O_d + \lambda_{cp} O_{cp} + \lambda_{cl} O_{cl}, \\ \text{s.t. } \forall p \in \mathcal{P}, |e_p - p|_2 \leq \varepsilon \\ \sum_{l \in L} l \geq \max\{|p - base|_2 : \forall p \in \mathcal{P}\}, \\ \forall l \in L,\ l \geq 0\end{gathered} \tag{1}$$

where l is a link of the WRL, ε is the tolerance threshold distance between the target points $\mathcal{P}$ and the end-effector positions e_p (reachability), and λ_s, λ_d, λ_{cp}, and λ_{cl} are the weights of the corresponding objective terms.

Since this objective function is non-convex, we use simulated annealing [50] to solve it. The reachability constraint is also integrated into the objective function as the ℓ_2 norm of the distance between the end-effector and the target point. To emphasize reachability, its relative weight is by default set to 1 in the interface, but the designer can adjust it according to the design considerations. As simulated annealing may converge to different local minima upon different runs for the same problem, we repeat it 10 times (with 1000 iterations each) and report the result with the smallest evaluated objective function.

For faster processing in the optimization steps, WRLKit clusters the captured body poses using their similarity in the stream of recorded poses. WRLKit does this by calculating the mean squared error between the joint position of the current pose and the first member of the current cluster. If this value is below an adjustable threshold, it adds the pose to the current cluster. Otherwise, it creates a new cluster and adds the current pose to it.

In the following, we explain the individual optimization objectives in more detail.

5.2 Minimizing On-skin Stress

As the WRL has to be mounted on the surface of the user's body, it exerts torques and forces at the mounting location, thereby putting undesired stress on the user's skin. To minimize the overall stress induced on the human skin by the WRL structure, we optimize the sum of squared weights and torques caused by the WRL structure. We formulate the cost function accordingly as follows:

$$O_S(L, J, \mathcal{P}) = |w(L, J)|^2 + \lambda_t \mathcal{T}(\mathcal{P}) \tag{2}$$

where $w(L, J)$ denotes the weight of the WRL and $\mathcal{T}(\mathcal{P})$ represents the torques introduced by the WRL to reach a set of target points $\mathcal{P}$ and λ_t is the normalizing factor defined as:

$$\lambda_t = \frac{1}{\sum_{i=1}^{|\mathcal{P}|} n_i} \tag{3}$$

To compute the torques exerted by the WRL, we first compute the exact 3D coordinates, $C(p_i, L) = \{C_j, C_l\}$, of the joints and link centers of mass in the robotic workspace for each pose cluster representative (cluster representative is the first user pose added to a new cluster while capturing user's motion patterns at 4.1). To that end, we first perform Inverse Kinematics ($\mathcal{IK}$) for the end-effector target position and then compute the joint and link positions using Forward Kinematics ($\mathcal{FK}$):

$$C(p_i, L) = \mathcal{FK}\big(\mathcal{IK}(p_i, L)\big) \tag{4}$$

WRL's structural materials apply stress on the user's skin at the mounting location.

Note, that not all configurations are equally likely to occur, and the more frequent poses (bigger clusters) are emphasized in our torque objective for the set of target points $\mathcal{P}$. We define $\mathcal{T}(\mathcal{P})$ as:

$$\mathcal{T}(\mathcal{P}) = \sum_{i=1}^{|\mathcal{P}|} n_i |T(C(p_i, L))|^2 \tag{5}$$

where n_i is the frequency of the configuration $C(p_i, L)$ calculated from the user's input poses stream and equals the size of the i^{th} cluster. Henceforth, we use C_i instead of $C(p_i, L)$ in our notations for the sake of better readability.

The torque at the base (mounting location) of the WRL has 3 elements about the local coordinate axes of the WRL's base, T_x, T_y and T_z. The objective function for stress optimization can therefore be expanded as:

$$\begin{aligned} O_s(L, \mathcal{P}) &= |w(L, J)|^2 + w_t \mathcal{T}(\mathcal{P}) \\ &= |w(L, J)|^2 + w_t \sum_{i=1}^{|\mathcal{P}|} n_i |T(C_i)|^2 \\ &= |w(L, J)|^2 + w_t \sum_{i=1}^{|\mathcal{P}|} n_i \big(|T_x(i)|^2 + |T_y(i)|^2 + |T_z(i)|^2\big) \end{aligned} \tag{6}$$

Finally, the overall weight $w(L, J)$ of the WRL can be calculated as the sum of weights of links (structural material) and joints (rotary motors):

$$w(L, J) = \sum_{l \in L} w(l) + \sum_{j \in J} w(j) \tag{7}$$

5.3 Reducing Drift

Each of the three elements of the torque about the local coordinate axis (T_x, T_y, T_z) can cause the WRL to drift about the relative axis at the mounting location on the user's body surface. The larger any of the torque elements about the axis in the base's local coordinate system becomes at one of the WRL's configurations, the higher the probability of drifting around the same axis is. The drift of the WRL can be attributed to the stretching of the skin and the eventual sliding of the base over the skin when the forces exceed the static friction between the skin and the mount. To reduce the probability of the drift, WRLKit optimization aims to reduce the upper bound on the maximum of every individual torque element:

$$O_d(L, \mathcal{P}) = |\alpha|^2 + |\beta|^2 + |\gamma|^2 \tag{8}$$

where:

$$\begin{aligned} \alpha &= max\{T_x(C_i) : i = 1, .., |\mathcal{P}|\}, \\ \beta &= max\{T_y(C_i) : i = 1, .., |\mathcal{P}|\}, \\ \gamma &= max\{T_z(C_i) : i = 1, .., |\mathcal{P}|\} \end{aligned}$$

5.4 Maximizing Compactness

By optimizing for compactness, WRLKit makes sure that the robot's workspace is closest possible to the user's body while WRL able to reach all target points. The workspace is spherical and the objective for compactness is defined as the volume of the workspace. To calculate the volume of the workspace, we intersect the spherical workspace with the human's body surface and calculate the spherical cap that is outside of the human's body. Hereby, we assume the human's body surface is locally planar at the mounting location:

$$\begin{aligned} O_{cp}(\mathcal{L}) &= Volume(spherical\ cap) \\ &= \int_0^R \int_0^{2\pi} \int_\Phi^\pi r^2 . \sin(\phi)\, d\phi\, d\theta\, dr + \pi \rho^2 \frac{h}{3} \\ &= \frac{1}{3}\pi R^3 (2(1 + \cos\phi) + \frac{1}{2} \sin\phi \sin 2\phi) \end{aligned} \tag{9}$$

where:

$$\Phi = \begin{cases} \arccos\left(\frac{l_1}{l_2 + l_3}\right) & \text{if } \frac{l_1}{l_2 + l_3} \leq 1 \\ 0 & \text{Otherwise} \end{cases}$$

$$R = l_2 + l_3, \quad \rho = R \sin\Phi, \quad h = R \cos\Phi$$

5.5 Minimizing Collisions with the Body

Some parts of the WRL structures possibly collide with the user's body for some of the poses. We aim to minimize such collisions. In order to have a continuous estimate of the collisions and their severity, the objective function for collision avoidance is defined based on the WRL segment lengths that are colliding with the humanoid body model. For each cluster of user poses and relative WRL configurations to reach at human-WRL target points, we define a vector function $\mathcal{F}_{collision}(h_i, C_i)$ that combines the human pose h_i and the WRL configuration C_i by calculating the sum of squared segments that are inside the human model's body surface.

$$\mathcal{F}_{collision}(h_i, C_i) = \sum_{l \in C_l} \sum_{s \in l \cap h_i} |s|^2 \tag{10}$$

The bigger the return value is, the more severe collision is happening. The collision avoidance objective function is defined as:

$$O_{cl} = \lambda_t \sum_{i=1}^{|\mathcal{P}|} \mathcal{F}_{collision}(h_i, C_i).n_i \tag{11}$$

where λ_t is the same as in Equation (3).

6 EXAMPLE PROTOTYPES

To demonstrate the practical feasibility of WRLKit and to illustrate its broad applicability for various types of interactions, we have used WRLKit to create different functional prototypes of WRLs, illustrated in Figure 5. In the following, we first detail on the iterative design process using one prototype and then briefly survey the remaining prototypes.

Upperarm-Mounted WRL for Haptic Feedback in VR. Haptic feedback can enable a more immersive virtual reality experience by engaging our sense of touch. Despite significant progress in this area, common vibrotactile grids are typically limited to a specific body area, whereas approaches with stationary robotic arms can only follow the mobility of the user to a limited extent. We, therefore, see WRLKit as a fruitful mobile approach to enable different flavours of haptic feedback on various parts of the body.

We created a WRL with WRLKit that provides on-skin tactile feedback on the forearm. It is worn on the upper arm and can give the tickling sensation with a brush end-effector that slides along the forearm (see Figure 5a). This can be used, for example, to simulate the crawling movement of a spider or touching a virtual soft object.

Using the graphical editor and optimization allowed us to quickly explore designs for haptic feedback on different locations on the forearm. We generated one for feedback on an area close to the wrist, and another for feedback close to the elbow. As depicted in Figure 6, the resulting WRL structures substantially differed in overall link length (57 cm for wrist vs. 41 cm for elbow), even though we kept the weights of the optimization criteria unchanged. This highlights the need for a customized design approach to generating WRLs. We then settled on the design for feedback on the wrist and continued to investigate personalization for different users. In addition to the existing design that was targeting a tall person (195cm), we captured another user with 165cm height. Again, we kept the weights of the optimization. The design for the second person differs quite substantially in terms of link length (47 cm for small vs. 55 cm for tall), again illustrating the need for a personalized approach, where WRLKit provides rapid assistance.

For actuation, we employed Dynamixel motors by Robotis controlled via serial communication (TTL). To provide power and movement commands to the servomotors, we also used the U2D2 communication module by Robotis. Figure 5a shows one of the final assembled prototypes. This example easily extends to other parts of the body (e.g. the hair with a WRL worn on the shoulder). Furthermore, with different end-effectors (e.g. from smooth brushes to sharper shapes), a variety of haptic cues could be conveyed at different spatial locations.

Hip-Mounted WRL for Assistance on the Go. A third arm can be very useful in tasks where both hands of a user are occupied. Using WRLKit, users can easily create personalized small, unobtrusive WRLs that can also be customised to support the demands of a specific task. As one example application, we have designed a WRL with WRLKit that is worn on the hip (see Figure 5b). It assists the user with pressing a switch or button when both hands are occupied. For instance, a deliveryman can use it, while holding a large and heavy object, to press a light switch, activate a door opener, or ring a bell. We used WRLKit to generate a WRL structure

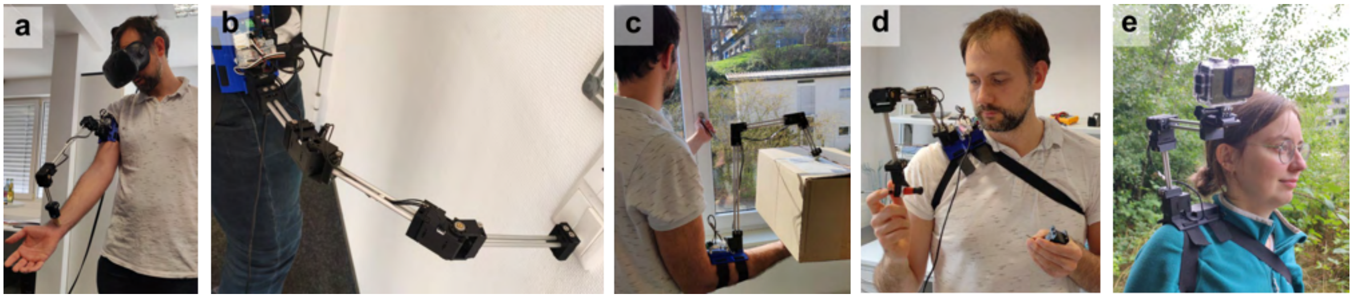

Figure 5: Personalized WRLs offer a broad spectrum of applications, ranging from novel ways of haptic feedback on the body (a) and providing assistance on the go (b) to helping to hold large objects with one hand (c) or tools in peripersonal space (d, e).

that is able to reach up to 52 cm. This is an example of how WRLKit can create WRLs that act in the peripersonal space of the user.

Forearm-Mounted WRL for Holding Large Objects. Another example, using WRLKit's capabilities for specifying on-body targets, is an assistive WRL that helps users hold a large object with a single hand (Figure 5c). This frees the user's second hand for other tasks.

Shoulder-Mounted WRL Offering a Third Hand. As illustrated in Figure 5d, WRLKit is also a valuable asset in quickly creating WRLs that can act as a third hand for holding an object in the user's direct reach, while the user's hands are both busy. In our example, we use a passive bistable gripper that can hold objects and tools of varied geometry.

2DoF Shoulder-Mounted WRL for Nature Recording. A 2 degrees-of-freedom wearable robotic arm with a camera mounted on it assists nature enthusiasts in recording immersive footage during journeys in nature. The device is shoulder-mounted. The robotic arm can flexibly adjust the camera's viewpoint along two rotary axes. (see Figure 5e)

7 USER EVALUATION

We conducted a user study to validate our proposed approach. Our main objectives are (1) to show that novice designers can effectively use the design tool to rapidly design a personalized WRL and (2) to identify strengths and limitations of the proposed approach from a user's perspective.

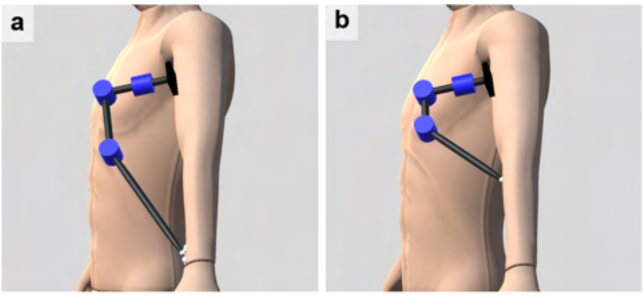

Figure 6: Comparison of two WRLs for haptic feedback on the forearm. Depending on the target being near the wrist (a) or elbow (b), the link length of the optimized WRL structures differ (57 cm vs. 41 cm).

7.1 Method

Participants. We recruited 6 participants (3 f, 3 m, 0 nb; M=26.5 y). They received a compensation of 10 Euros. Three participants are HCI researchers with experience in soft robotics (P1), conventional robotics (P2), and on-body robotics (P3). We also recruited three interaction designers with a background in computer science (P4, P5) and psychology (P6) who do not have prior experience in robotics.

Procedure. The study took place in single-user sessions and took about 40 minutes per participant. The study was modelled after comparable studies that evaluate design tools, e.g., [27], and was video recorded. First, the experimenter explained the tool's functionalities. Next, the participant was tasked to use our tool to design a WRL for one of the applications presented in Section 6. We encouraged them to ask questions, and the experimenter helped out or intervened when problems occurred. After having completed a first design, the participants could select another application for which they design a WRL using the tool until they were satisfied with the outcome. They were asked to think out loud, while the experimenter silently observed them and took notes. We ended this session with a 7-point Likert scale SUS questionnaire [6] and a semi-structured interview to elicit feedback and suggestions for future improvement.

Data Analysis. We gathered qualitative (videos of users, notes of the silent observation, interview transcripts) and quantitative data (7-point Likert scale SUS and task completion time). To better understand user's reactions to the tool as well as particularly positive and negative aspects of the design pipeline, we analyzed the qualitative data through open coding using MAXQDA. We report on participants' quantitative data for contextualization.

7.2 Qualitative Results and Feedback

All participants successfully designed at least one WRL for one of the applications in Section 6 using the tool without help from the experimenter and provided valuable feedback. We summarize the central findings below.

Ease and Effectiveness of the Tool. Once learned, participants took on average 7 minutes (Min=4, Max=14, Mdn=5 mins) to finish a WRL design without intervention from our side.

In their questionnaire responses, participants indicated that the tool was learned rather quickly (Q7, Mdn=5.5, M=5.5 where 5 means "somewhat agree" and 6 "agree"). Participants further were in favor of the tool as it is easy to use (Q3, Mdn=6, M=5.5), *"simplifies the thinking process"* (P5), and frees them from doing the mechanical engineering themselves, which would have consisted of manual *"trial and error"* otherwise (P2). However, they suggested to further improve the UI design such that it better informs about its functionalities and will be even quicker to learn. This underpins that our tool enables novice designers to rapidly design a WRL, and that this process is substantially faster than manual design.

Capture Body Dimensions and Motion Patterns. Participants appreciated that the tool captures the user's body poses: *"For different uses you need different movements and you want to make sure that the [wearable robotic] limb is not restricting the person in any way"* (P6). P1 realized that she would not have considered these body poses during manual prototyping for its complexity, *"because [. . .] trying to think about how we would be able to reach the whole space and optimize the link size is hard".* While motion capturing takes a lot of work off the designers' shoulders, P2 and P6 suggested that the tool should also allow *"to refine [the recorded motions] in certain poses"* (P2) using the interface avatar which would be helpful in cases where task specifications change during the design process.

Specify Design Parameters. Participants stated that freely specifying the mounting locations and the robot's workspace is *"extremely helpful"* (P2) and *"really intuitive"* (P6). Particularly participants with a background in haptics (P1, P2, P3) appreciated the option to define targets on the body. One participant notably struggled with the concept of defining a target relative to the body (application 6), because it abstracts from the real world: *"There was confusion because there was no doorbell [. . .]. How can I design something for a doorbell, if the object is not there?"* (P2). Consequently, less abstract representations and simulations might help to better inform the user's design decisions (e.g., the exact position that the end-effector should reach) and further improve the workflow.

Optimize the WRL Structure. Participants quickly were able to weigh how to prioritize the optimization criteria: *"It was really nice that I could choose the priority I want to put on their body stress and on the on-body drift because depending on the position of the limb, it differs how much of a priority I want to put there"* (P6). Although participants were satisfied with the offered optimization criteria, four participants wished for instant feedback that immediately visualizes how the WRL structure is influenced once a weight is changed, rather than waiting around 5 seconds after pressing "generate". This suggests that participants can reason about their choice of optimization criteria generally, but the effect of optimization weights on WRL design needs further clarification.

Inspect and Iterate. Several participants explicitly appreciated the simulation of WRL configurations relevant to body poses that allow them to inspect their design, because *"then I realized that it does not make sense to have the [robot] up here [refers to the specified workspace]"* (P2), and *"I didn't have to think too much about whether this arm can reach where I want it to be"* (P5). Whilst the simulation supports participants to uncover problems, some initially had trouble understanding the purpose of the green points in the UI (P2, P4), also because *"it [looks] a bit clustered"* (P3). The confusion could be quickly resolved through the experimenter's explanation.

Further Improvements. There were a few other suggestions for future improvement of the tool: Two participants suggested offering more joint types and end-effector plug-ins for different application areas. Three participants of whom two had prior robotics experience wished for the possibility of adding their expertise to the generated WRL design by defining their own constraints for the optimization: *"I intuitively wanted to move the links and adjust the sizes of them myself as [. . .] what I think it should look like, and then have it optimized around it"* (P1). In the future, the tool could offer the option to define such constraints, allowing for a co-creation that combines the strengths of both, experts' experience and the tool's abilities to optimize for complex configurations.

7.3 Discussion

Giving Control of Design Choices to the User. WRLKit aligns with the current research trend of keeping designers in the loop during the computational design process (e.g., [27, 33, 38]). WRLKit offers the designer a good level of control throughout various parts of the pipeline, which was appreciated by the study participants, notably the option to freely define on-body or off-body targets, mounting locations all over the body, or defining the weights of the optimization criteria. However, there are even more possibilities to customize the outcome. Therefore, we recommend that future tools should offer more real-time interactivity in the optimization process (cf., [9]) as suggested by two of the three expert participants, and also offer a broader range of options to customize the physical design (e.g., end-effectors and joint types).

Usefulness of Motion Capturing and Computational Features. WRLKit adds to the emerging body of motion-capturing tools, e.g. [27], that make the design of robotic devices feasible for non-experts. The motion-capturing offered by WRLKit integrates the captured data directly into the optimization process, which would be a time-consuming and highly complex – if not even impossible – task both for experts and novices when being done manually. Following the study results, we recommend to further improve the usefulness of the motion-capturing step through a closer link between the captured real-world data and design options in the tool. This includes, e.g., a motion editing tool that allows to edit previously recorded postures (see e.g. [33]).

Further, the optimization criteria offered by WRLKit empower designers to reason about which criteria are more relevant for their application on a high level without requiring domain expertise. To bridge the gap between high-level reasoning and the generated design, we recommend that future tools should better explain to designers how optimization weights affect generated results.

Relevance of Scene Representation and Behavior Modeling. The motion capturing step offered by WRLKit bridges real-world input and in-tool representation, as users can directly demonstrate the desired motions in the real world and inspect them in a 3D avatar representation afterwards. Regarding the in-tool representation of the task and output of the generated WRL design, for future work, we recommend to (1) simulate the generated design with more contextual information (e.g., the geometry of objects manipulated by the WRL) and (2) visualize the design in situ on the user's body (e.g., through virtual or augmented reality) to fully close the loop between real-world input, in-tool representation, and tool output.

8 LIMITATIONS AND FUTURE WORK

While our work demonstrated that interactive computational design is a powerful means for rapidly generating personalized WRLs, this first study is subject to several limitations:

Generated WRL Hardware. As the scope of the WRLKit focuses on rapid prototyping customized WRLs with accessible fabrication methods, the produced WRLs, rather than being high-fidelity prototypes, are serial mechanisms built by commodity rotary actuators, 3D-printed mounts and laser-cut links. Our current version is limited to a max. of 3 DoFs with 4 links and to passive end-effectors.

While we selected the servomotors for their favorable torque-to-weight ratio, attainability and ease of use, without requiring much engineering knowledge on electronics and control theory, Users may choose different motors based on their requirements.

Our current prototype uses motors with high gear ratios and does not provide a very high backdrivability, as our initial aim is to provide a robust position control performance to the WRL structure. Lower inertia motors should be considered to control the structure in large range of impedances.

Design Tool and Optimization. Our optimization step currently only accounts for the static forces stemming from the weight of the WRL. It does not consider the loads at the end-effector, as these are influenced by the dynamic real-time control of the robot and the specific object it manipulates. Moreover, we are currently not considering dynamics. Future implementations should allow the designer to model the object that the WRL will manipulate in terms of its geometry, mass and deformability. Our design tool currently optimizes the WRL to be able to always reach the entire defined workspace, independent of the user posture. Considering a specific desired motion trajectory, depending on user posture, is an interesting addition. Also, future work might consider optimizing the shape of the mounting unit to further improve the fit to the selected mounting location.

Real-time Control. We acknowledge that real-time control is outside the scope of this paper, which focuses on creating the hardware structure of a WRL. Allowing the designer to model the expected real-time behavior of the WRL directly inside the design tool is a very interesting direction for future work. We expect that a virtual or augmented reality-based design environment may present very interesting opportunities for direct and intuitive specification of the WRL's real-time behavior.

Safety. Our current pipeline addresses safety of the generated WRLs by minimizing potential collisions between the WRL structure and body parts for the recorded poses.

While motors and links are robust for a wide variety of applications, this does not jeopardise the safety of the user, as at higher forces the elasticity and movement of the skin and body tissue first cause the base unit to move in the opposite direction before harmful forces are applied to the user.

Capturing the Richness of the Body. While our markerless motion capture setup allows for one-shot and convenient recording of body dimensions and poses, the current implementation is subject to several limitations. Our current model does not account for rotations of limbs around their longitudinal axis. While we can anecdotally report that this did not present problems of our presented application cases, it may be relevant in other tasks. We plan to include sensing of rotations with a wrist-mounted IMU, such as deployed in a smartwatch. Furthermore, our implementation does not model an individual user's body surface geometry. Using monocular dense reconstruction methods like [14, 17, 32, 48] is very promising. Lastly, incorporating a dynamic camera setup would help enhance our applications beyond stationary tasks.

Explorative Study. While our user study has demonstrated the effectiveness of the tool and explored first aspects to be addressed in future work, it was limited to the design process. To avoid overly long study sessions, the generated designs have been fabricated and assembled by the authors after the study session. Second, future studies should involve a larger group of users that can use the tool in longer trial sessions to design WRLs for any application of their choice. This would help to understand in more detail how the tool will be used by end-users for various application cases and to identify further customization options that support the user.

9 CONCLUSION

This paper presented WRLKit, a novel design approach that enables interaction designers and application experts to rapidly prototype personalized wearable robotic limbs (WRLs) adapted for different tasks and to the unique proportions of a body. Our body-centric approach captures the user's body dimensions and dynamic postures and generates an optimized manufacturable WRL structure for a desired mounting location and set of targets in space. The results of a user study and several implemented prototypes demonstrate the practical feasibility and versatility of our approach.

With WRLKit we contribute to the vision of WRLs as a fruitful extension of the human body. We aim to make WRLs more accessible to non-roboticists, enabling them to explore the exciting field of WRLs and develop innovative designs and applications.

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