StretchAR: Exploiting Touch and Stretch as a Method of Interaction for Smart Glasses Using Wearable Straps

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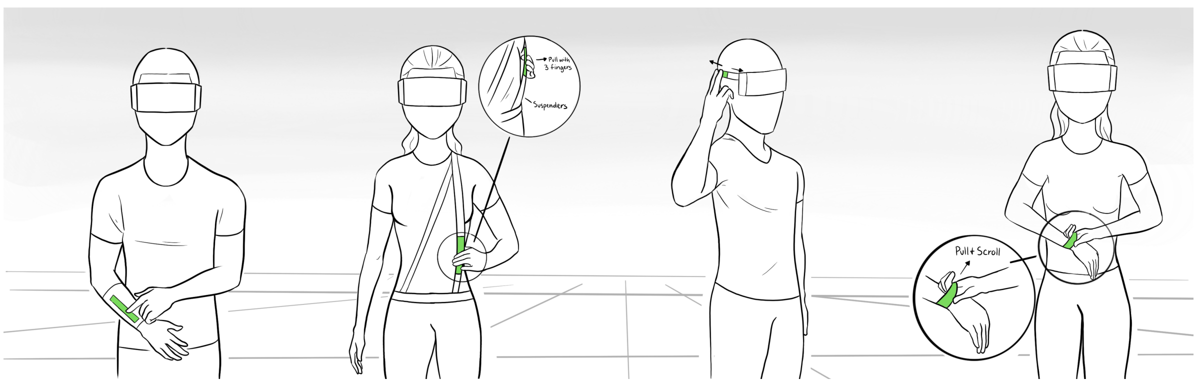

Fig. 1. Representation of touch and stretch interactions for smart glasses using StretchAR on different body locations (From left to right) : Forearm, Chest, Head, and Wrist

Over the past decade, augmented reality (AR) developers have explored a variety of approaches to allow users to interact with the information displayed on smart glasses and head-mounted displays (HMDs). Current interaction modalities such as mid-air gestures, voice commands, or hand-held controllers provide a limited range of interactions with the virtual content. Additionally, these modalities can also be exhausting, uncomfortable, obtrusive, and socially awkward. There is a need to introduce comfortable interaction techniques for smart glasses and HMDS without the need for visual attention. This paper

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presents StretchAR, wearable straps that exploit touch and stretch as input modalities to interact with the virtual content displayed on smart glasses. StretchAR straps are thin, lightweight, and can be attached to existing garments to enhance users' interactions in AR. StretchAR straps can withstand strains up to 190% while remaining sensitive to touch inputs. The strap allows the effective combination of these inputs as a mode of interaction with the content displayed through AR widgets, maps, menus, social media, and Internet of Things (IoT) devices. Furthermore, we conducted a user study with 15 participants to determine the potential implications of the use of StretchAR as input modalities when placed on four different body locations (head, chest, forearm, and wrist). This study reveals that StretchAR can be used as an efficient and convenient input modality for smart glasses with a 96% accuracy. Additionally, we provide a collection of 28 interactions enabled by the simultaneous touch–stretch capabilities of StretchAR. Finally, we facilitate recommendation guidelines for the design, fabrication, placement, and possible applications of StretchAR as an interaction modality for AR content displayed on smart glasses.

CCS Concepts: • **Human-centered computing** → **Mixed / augmented reality**; **Interaction techniques**.

Additional Key Words and Phrases: Wearables, stretchable electronics, augmented reality, cyber-physical systems, Human AR interaction, interactions

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1 INTRODUCTION

Smart glasses and head-mounted displays (HMDs) augment the surroundings of the user with superimposed digital content—such as images, text, videos, and 3D virtual objects. This virtual content can provide information about real objects and even expand their functionalities by creating real-time interactive and realistic experiences [15]. During the last decade, cellphones and tablets have served as convenient platforms to implement a variety of AR applications. However, recent advances in the miniaturization of electronic and optical components have moved the focus towards the implementation of AR experiences using wearable and aesthetically acceptable smart glasses and HMDs. Unfortunately, AR users are still required to learn methods to interact with and manipulate the virtual content, given that their hands do not interface directly with a tactile screen. Several methods have been developed to allow the AR users to interact with smart glasses and HMDs [49]. The most popular approach implemented in the majority of commercially available HMDs [10], is the use of mid-air gestures. Gesture-based interaction, however, is complex, causes arm fatigue, and is not convenient to use in a social environment [37]. The use of voice commands and predefined verbal instructions has also been explored to enhance human-AR interaction. Unfortunately, voice-based interaction often requires memorization of commands, suffers from contextual limitations, compromises privacy, and can be disturbing to others [19]. Other AR systems superimpose virtual widgets on the body of the user, who can use them as interfaces via mid-air gestures or tactile inputs. These AR widgets, however, require the complete visual attention from the user, disrupting the pace of the AR experience [5, 44]. To add functionality and overcome these limitations, handheld controllers provide several interaction channels in the same device. These AR controllers, however, are required to be constantly carried by the user and thus, restrict the free movement of the hands and impeding the development of daily activities [21, 28]. Additionally, hand-held controllers are often rigid, hindering the user from exploiting stretching as a method of interaction with AR content. The development of an interactive interface capable of being embedded into the garments or accessories of the user would be desirable to facilitate the rapid access to virtual information and the interaction with AR content.

Recent advances in wearable electronics and smart textiles have facilitated the inclusion of a variety of sensors in the garments of the users, creating seamless and ubiquitous human-AR interfaces [25, 39]. The versatility of these smart textiles allowed for the exploration of new interaction methods by combining design and functionality on a variety of daily-use clothes and apparel, such as gloves [5, 87], pockets [17], patches [77], sleeves [67, 69], and other accessories such as zippers [46], belts [16], and cords [44]. The use of the body as a portable and accessible surface for interaction has also motivated the creation of skin-like interactive interfaces. These on-skin electronics, also called e-skins, provide interactive capabilities to the body of the user, who can achieve fast and eyes-free human-AR interactions using tactile inputs [33, 41, 54, 83]. Unfortunately, the low thickness of e-skins renders these interfaces fragile, limiting their usage to single-use. Moreover, wearable human-AR interfaces, are often specific to a single body location or linked to a particular garment, complicating their customization and limiting their adaptability to different outfits and environments. Furthermore, both garments and skin-mounted human-AR interfaces usually exploit touch, on 2D surfaces, as their main interaction method since this method is considered the most intuitive due to the popularized access to information through flat-screen interfaces. Since smart glasses and HMDs provide the user with 3D virtual content, the use of 2D inputs rapidly become insufficient to ensure a seamless human-AR interaction. We envision that taking advantage of the stretchability of smart textiles would provide intuitive approaches to interact with the 3D virtual content displayed by smart glasses.

This paper explores the design space of stretchable smart-straps as an input modality for human-AR interfaces to enable fast and eyes-free interaction between wearers and their smart glasses. We call this common unisex smart accessory "StretchAR", stretchable straps designed to be worn by users with different body types and attachable onto a large variety of outfits. The bendability and stretchability of StretchAR enable new personalized input modalities for smart glasses, combining touch and stretch to capture input intentions from the users. We conducted a user study with fifteen participants to evaluate the interaction potential that the combination of touch and stretch inputs can provide for wearable human-AR interfaces. StretchAR also supported understanding of the physical constraints of implementing touch and scroll inputs using a deformable wearable attached to users on different body locations. The user study was divided into two tasks. The first task evaluates stretch-touch interaction to manipulate content in a horizontal virtual menu selection, and the second task studies a touch-scroll interaction to access information on rotational virtual menus. We evaluated the accuracy, efficiency, and comfort of StretchAR in four body locations: head, chest, forearm, and wrist **(Figure 1)**, and identified the influence of body locations and touch configurations during the interactions. The contributions of our paper are as follows.

- The development of StretchAR, wearable smart straps that allow users to intuitively and accurately interact with the AR content displayed by smart glasses and HMDs using tapping, scrolling, and pulling gestures.
- Recommendations and guidelines for the design and fabrication of conformable StretchAR.
- Analysis and discussion of a user study identifying the advantages and limitations of combining stretch and touch as input modalities for smart glasses.
- Demonstration of 28 StretchAR-enabled human-AR interactions achieved by placing the StretchAR on head, chest, forearm, and wrist of the user.
- Development of three AR applications where StretchAR provide meaningful and intuitive human-AR interactions.

We envision the stretch-touch input modalities unveiled by StretchAR will enhance user interaction with AR content for smart glasses, paving the way for the next generation of wearable and stretchable human-AR interfaces.

2 RELATED WORK

2.1 Interactive Methodologies to Interface with Smart Glasses

Effective interaction with digital content displayed on smart glasses remains challenging for many users, as current approaches for selecting, moving, and manipulating virtual content are often cumbersome and not intuitive [49]. The ways users interact with the virtual content depend not only on the type of content but also on how the content is displayed. Therefore, AR information is commonly displayed using virtual menus with different geometries [15], virtual screens for 2D virtual interfaces [56], or superimposed 3D content [44]. The large variety of AR content and approaches to display this content requires exploring new interactive methods that simplify human-digital communication. Current AR interaction modalities can be grouped into four main groups: on-body projected interfaces, mid-air gestures, hand-held controllers, and wearables.

On-body projected interfaces allow users to use touch-based interactions to interact with virtual content using virtual menus and discrete options displayed as holograms on hands [4, 5, 57, 58], forearms [3, 5, 33, 51], chest [62], legs [5], and feet [59]. Other on-body interfaces effectively exploit head movements and natural face-touching to interact with AR content [1, 55, 73–75, 85]. This combination of body-part identification, display of visual menus, and gesture identification is, however, computationally intensive and limited to a discrete set of interactions that require the complete visual attention of the user, hindering immersive AR experiences.

Mid-air gestures utilize hand poses and movements to create commands and manipulation strategies to interact with virtual content. Some AR systems, such as Ubii and FingARtips, use computer vision to track the hands of the user and identify gestures that allow interaction with the virtual content displayed in smart glasses [6–8, 52]. Other AR systems use cameras worn on the chest or the head to identify distinctive hand patterns [11, 13, 34, 50] or head movements [47]. This input modality can be extended to other limbs and actions, allowing the users to interact with virtual content with their feet and navigate through virtual scenarios by walking in different directions [59, 60]. Despite the benefits and convenience of gesture-based interactions, their extensive use is exhausting, reducing input accuracy across prolonged periods. Additionally, some of these gesture-based interaction modalities require considerable visual attention [36, 40].

The use of multifunctional hand-held controllers to interact with AR content has gained popularity owing to the high accuracy of their different interaction modalities [45, 68]. Due to their availability and their touch and orientation sensitivity, phones and tablets have become the most used hand-held devices to interact with virtual content [28, 71, 91]. Other specialized controllers with judiciously chosen geometries such as spheres [21, 22, 72], mechanically flexible two-hand controllers [24], wands [30], and haptic devices [32] facilitate human-digital interactions such as the rotation and manipulation of virtual objects. Unfortunately, the use of hand-held controllers limits portability and reduces the comfort of the user by obstructing natural motions.

StretchAR accesses fast and natural on-body interactions based on user preferences by being attached to various garments in different body locations. Additionally, it enables access to AR information, data, and content displayed through smart glasses.

2.2 Wearables and Smart Textiles Interacting with Smart Glasses

The design, function, and on-body location of wearable devices enable multiple forms of interaction with virtual content [43]. Wearables expand the interactability of different body parts, providing more alternatives to the users to communicate with AR content than traditional touch and mid-air gestures. To maximize interaction with the AR content displayed by smart glasses, miniaturized sensing elements are either directly attached to body parts or embedded into garments known as *smart textiles*. Hands are the most popular channel of interaction with AR content. In prior work, hands have been instrumented with self-adhesive sensors [64], smart rings [23, 66, 84], smart gloves [37, 61, 96], and cameras [70] to facilitate the interaction with AR content displayed by HMD via finger pressure, shear, and pinch gestures. Similarly, other on-body locations easily accessible by hands, such as the forearms [65] and the head [23], have also been used by wearable devices to facilitate the navigation and interaction with virtual AR menus and widgets.

Recent advances in flexible electronics have favored introducing complex sensing elements into textile-based substrates, leading to the development of smart textile interfaces. For instance, Project Jacquard [69] introduced a touch-based sensor that could be integrated into jackets, backpacks, and insoles to allow users to control IoT systems with hand gestures. Belt, another unobtrusive touch-enabled smart wearable, exploits finger tapping and swiping input modalities along the waist for menu navigation and interaction with AR content on smart glasses [16]. Other smart textiles such as smart cords [44] and pockets [17] allow users to use the sliding of their fingertips to navigate through the AR content displayed by smart glasses in a convenient and discrete way. Strechar explores the possibilities of additional interactions and applications that the stretch and touch combination can enable as an input modality for smart glasses. This exploration will also consider the use of different body parts and interaction configurations to expand the design space and available interaction modalities for smart glasses and HMD's.

2.3 Stretch and Touch as Interaction Methods for Smart Glasses

Touch-based interactions represent the main input modality for smart glasses and HMDs since the users perceive them as an intuitive and easy to adopt to interact with AR interfaces. Applications such as navigation of menus [5, 65, 69, 92] and environment manipulation [11] commonly benefit from touch-based interactions. For example, *Mind the tap* explores a touch-based and hands-free interaction method that allows users to interface with virtual menus using their feet [59]. Smart glasses also benefit from touch-based interactions through multiple approaches to type, such as *Digitouch* and *PalmType*: Digitouch [87] uses a two-hand text input method that distributes a QWERTY keyboard across both palms of the user. Similarly, PalmType [82] distributes a QWERTY keyboard on one hand, allowing the other hand to be used to type. Overall, touch-based interaction have proven to enable rapid reactions and content selection [70, 83, 94]. However, touch input interfaces are limited to convenient accessible areas and often require visual attention [5], which reduces the number of practical alternatives for touch-based interaction.

Stretch-based inputs remain mostly unexplored as an interaction method that leads to rapid and direct responses to the AR content displayed by smart glasses. Stretchable sensors, such as StretchEBand [81] and other stretchable electronic systems [93], have lead to the advancement of smart textiles and wearable devices, as the incorporation of strain-insensitive sensors has improved on-body measurements [26]. Stretchable electronics systems to interact with AR content have mainly focused on capturing hand poses [12, 27], pull detection [29], bending [42, 48], breathing measurements [88], or the monitoring of robotic articulations [78]. While touch and stretch have been successfully used before as independent methods of interaction with AR content, this work seeks to explore how the combination of stretch and touch—using StretchAR—can expand the range of interactions currently compatible with smart glasses and HMD.

3 StretchAR DESIGN

StretchAR is a strap-like wearable capable of simultaneously detecting touch and stretch input modalities. We designed StretchAR as a lightweight and stretchable strap to enhance its conformability, wearability, and allow single-hand manipulations. The thin geometry of StretchAR facilitates the integration of the stretch-touch interaction modality into multiple body locations and garments. The strap form factor of StretchAR makes it a gender-neutral and age-independent interactive accessory, which can be easily attached or embedded into a large variety of garments to meet the style requirements of the user.

3.1 Functional Layers of StretchAR: Design and Choice of Materials

Figure 2 shows the multilayer approach used to facilitate the integration of different sensing elements of StretchAR (see Figure. 2). StretchAR comprises three functional layers: i) A stretch-independent, touch-sensitive layer (top); ii) a touch-independent, stretch-sensitive layer (middle); iii) a layer of stretchable sewn electrodes transmitting the touch/scroll input collected by the top layer to the external microcontroller (bottom). Manufacturing StretchAR using this approach facilitates the assembly of the smart strap and ensures the independence of the touch and

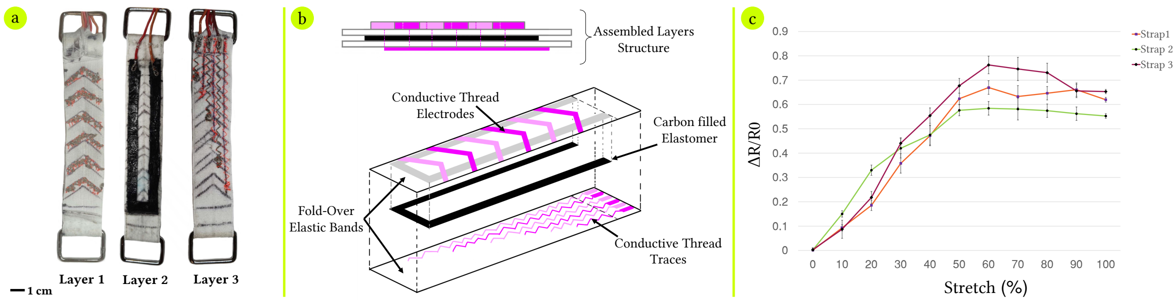

Fig. 2. (a) Top-view of each of the three layers of StretchAR: Layer 1 shows the conductive thread electrodes designs to detect multifinger touch and scrolling. Layer 2 shows the elastomeric conductive electrode used to quantify stretching. Layer 3 shows the stretchable sewn thread used to interface with the touch-sensitive electrodes of Layer 1. (b) Exploded schematics indicating how StretchAR are assembled. c) Dependence of the relative resitance ($\Delta R/R_0$) of the stretch sensor on the strain (ϵ) applied.

stretch sensing elements. When choosing a textile substrate for StretchAR, we opted for a one-inch fold-over elastic band (9487W, from Dritz Inc. [18]) due to its stretchability, softness, relatively low cost, breathability, and the ease with which it can be sewn and cleaned. Additionally, the porosity of the fibrous structure of this elastic band is appropriate for the screen-printing of conductive elastomers and the securing of electrical contacts using conductive epoxies. This elastic band stretches linearly along its main long axis (up to strains, $\epsilon = 190\%$) and shows minimal stretching in its perpendicular axis. Future versions of StretchAR could benefit from choosing other textiles as a stretchable substrate to take advantage of the non-linear deformation and provide the user with intuitive haptic feedback during human-AR interactions. Therefore, other materials—such as spandex, power mesh, and directional and non-linear textile-based elastic bands—could be considered for the fabrication of StretchAR due to their mechanical properties and their simple integration into garments using manufacturing techniques commonly used by the textile industry.

We manufactured the six stretchable contact pads used for touch and scroll detection on the top layer of StretchAR using automated machine embroidery (Singer M3400). The design of these touch-sensitive pads aimed to enable the accurate recognition of touch and scroll inputs independently of the stretching of the underlying elastic band (see Figure.2b). We chose a conductive nylon thread coated with a 1μm-thick layer of silver [14] to embroider the contact pads (top layer) and to sew, in a zig-zag pattern (width=3 mm, length= 4 mm), the electrical contacts of the touch-sensitive pads (bottom layer). We chose this conductive thread because of its high conductivity, reduced rigidity, and softness, which minimizes jams in small and portable sewing and embroidery machines.

To fabricate a stretchable sensor that could quantify the level of stretching of the underlying substrate (middle layer), we choose Elastosil LR 3162 [20], an electrically conductive, silicone elastomer. We screen-printed the Elastosil prepolymer through a laser-cut stencil directly over the textile-based elastic band used as a substrate. The Elastosil prepolymer readily adhered to fibrous structure of the elastic band and, after curing at 65°C for 5 minutes, created a U-shaped stretchable channel whose electrical conductivity decreases proportionally with its stretching (up to elongations of ϵ= 340% [95]). The low thickness of the Elastosil channel (~ 200 μm) facilitates the integration of the stretch-sensitive middle layer of StretchAR by stacking. We monitored the change in resistance of the Elastosil channel during stretching, which allowed us to quantify the strain sustained by StretchAR. We recommend avoiding off-the-shelf thread-based stretch sensors as their sensitivity to large strains is not uniform [35].

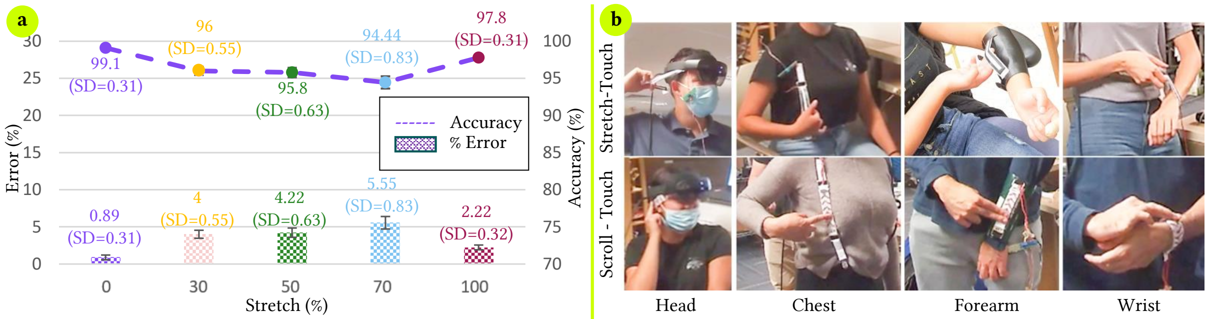

Fig. 3. a) Dependence of the accuracy of the stretch sensing layer of StretchAR on the value of the stretch. Error bars indicate nine measurements (three StretchAR prototypes used with one, two, and three fingers). The accuracies plotted have a ±1 tolerance. b) Human-AR interactions enabled by StretchAR on different body locations.

3.2 Interaction Principle

Figure 3 shows how the layered functional structure of StretchAR enables the combination of stretch and touch as interaction methods on multiple body locations (head, chest, forearm, and wrist). To use StretchAR, users only need one hand to touch/hold the strap and pull it outside their bodies. The strap provides continuous sensing of stretch and simultaneous multi-finger touch/scroll detection, only requiring the user to completely release the strap to confirm a stretch input value. Suppose the user exceeds the desired stretch input and wants to reduce it to a smaller value. In that case, the value automatically updates when the user releases the strap gradually without interrupting the touch interaction on the top layer of StretchAR. When pull or scroll interactions are not convenient for the user, StretchAR can be used as a touch-sensitive surface attachable to various body locations, using multi-finger tapping to select and confirm a selection. Additionally, StretchAR allows users to perform long touch interactions, which can be useful to open main menus and access the configuration options of IoT devices or smart glasses.

3.3 Evaluation of the Performance of StretchAR

We technically evaluated the performance of StretchAR, combining stretch and touch inputs, and touch and scroll inputs. These tests allowed us to define the accuracy of these interaction modalities, and the working ranges prior to our user study.

3.3.1 Stretch-Touch Test: The test measures the change in resistance and accuracy of StretchAR, quantifying applied strain and identifying touch inputs. To perform the experimental evaluation, we built a structure that supports the strap while performing the touch-stretch interactions. The structure holds both ends of the strap and allows the pulling action to be executed from its middle section. At the beginning of the test, the structure detects 0% stretch (0 mm vertical deflection). At 100% of stretch, the structure detects 54.9 mm vertical deflection. We defined the three intermediate stretch values of 30%, 50%, and 70% based on the measurement range. To characterize the accuracy of StretchAR, we collected 50 measurements for each stretch value (0%, 30%, 50%, 70%, and 100%.) using 1, 2, and 3 fingers, leading to a total of 750 measurements (i.e., pulling the strap with 1 finger at 50% stretch generated 50 data points).

We tested three prototypes of StretchAR, all of which exhibited a linear relationship between the change in resistance and the stretch in the range ϵ=0%–60% (see Figure 2c). Between ϵ= 70% and 100%, the non-linear change in resistance of the conductive elastomer become significant. To avoid non-linearities during the user evaluations, we used stretch values ranging ϵ=0%–60% to detect the stretch-based interactions. We attribute the

Table 1. Tables displaying: a) Confusion matrix indicating Finger Prediction during stretch-touch accuracy evaluation for a distribution with 750 samples, Misclassification = 30, b) Confusion matrix indicating Finger Prediction during scroll-touch accuracy evaluation for a distribution with 300 samples, Misclassification = 12, and c) Confusion matrix indicating Scroll Prediction during scroll-touch accuracy evaluation for a distribution with 300 samples, Misclassification = 10

	Predicted				Accuracy (%)
	# fingers	1	2	3	
Actual	1	242	8	0	96.80
	2	5	238	7	95.2
	3	3	7	240	96.00
a) Overall accuracy (%) Stretch-Touch					96.00

	Predicted				Accuracy (%)
	# fingers	1	2	3	
Actual	1	97	2	1	97.00
	2	2	96	2	96.00
	3	1	4	95	95
b) Overall accuracy (%) Scroll-touch					96.00

	Predicted			Accuracy (%)
	scroll direction	scroll up	scroll down	
Actual	scroll up	146	4	97.33
	scroll down	6	144	96.67
c) Overall accuracy (%) Scroll-Touch				97

(grey)	True positives & True negatives
(pink)	False positives & False negatives

small variability found when comparing the measurements across prototypes (Figure 2c) to the manual layering process used to fabricate the stretch-sensing layer. The accuracy of the three StretchAR prototypes to detect the correct level of stretch was 91.8% (SD = 2.62) with no tolerance considered, and 96.63% accuracy with ±1 tolerance (Figure 3a). Additionally, the average accuracy of StretchAR in detecting the number of fingers while stretching was 91.07% (SD = 0.83). We then calibrated the touch electrodes to improve finger detection for each of the users. After this calibration, the accuracy of detection of the number of fingers used to stretch the strap was 96% (SD=0.68).

3.3.2 Scroll-Touch Test: We conducted a scroll-touch interaction test with the three StretchAR prototypes to define the accuracy of the detection of scrolling direction and the number of fingers used to scroll. The scroll-touch interactions were executed with one, two, and three fingers scrolling in two different directions (up and down). At the same time, both ends of the StretchAR remain fixed. We collected fifty data points for each combination of the number of fingers and scroll direction, achieving 300 measurements for the test. The average accuracy of scroll detection was 92.67% (SD = 1.89) before calibration, and 96.66% (SD = 0.67) after calibration. The accuracy of the number of fingers detection was 92.44% (SD = 1.02) before individual calibration, and after calibrating the touch sensor to each user, the average accuracy was 96% (SD = 0.81).

4 USER STUDY

4.1 Methodology

We conducted a user study to determine the feasibility, usability, and accuracy of StretchAR as interaction method for smart glasses and HMD. We systematically evaluated the study results to define the interaction modality and elicit design guidelines that will allow StretchAR to succeed as a form of interaction.

This user study aims to identify the influence of body placement, touch, and stretch on the accuracy and speed of human-AR interactions. Additionally, the study collects the forms that participants intuitively used to interact with StretchAR while attached to different body parts (head, chest, forearm, and wrist). Fifteen participants were recruited (six female, nine male) with ages between 21 to 28 years old (mean 23.1, SD 2.4), in line with previous evaluations of wearable technology [53, 59, 80]. Only three participants had previous experiences with smart glasses or AR applications; the rest had a basic knowledge of AR/VR applications. The study was performed in an indoor location and was simultaneously video and screen-recorded for post-analysis. First, we described the tasks to the participants and trained them to use StretchAR. During the training process, the values registered by the StretchAR were offset according to the capacitive baseline of the user. Each task required the participants to execute a sequence of gestures combining touch and stretch. Touch inputs included multi-finger tapping, holding,

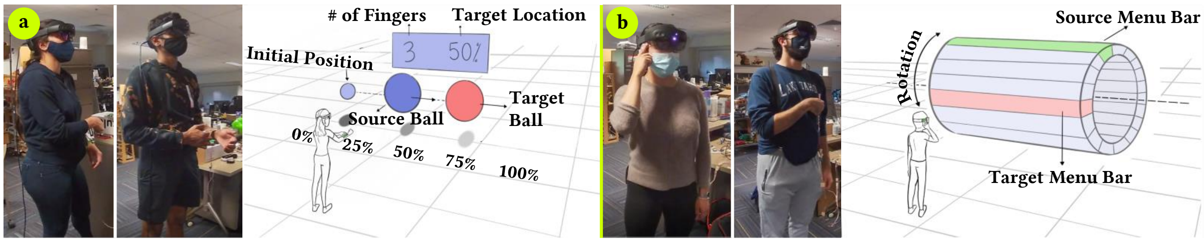

Fig. 4. Evaluation tasks in the user study. a) Task 1, stretch-touch: Images showing the task setting and the participants performing forearm and wrist stretch interactions, b) Task 2, scroll-touch: Setting and participants performing head and chest scroll interactions.

and scrolling actions. Each task was repeated on the different body locations (head, chest, forearm, and wrist Figure.3b). We randomly counterbalanced the body locations across participants, ensuring that each sequence was unique. After completing each task in each body location, the participants filled out a survey that contained Raw NASA TLX [63], the willingness to use (0–100) scale, and the convenience level (0–10) scale. At the end of the study, each participant took a conversation-type interview to provide subjective feedback, interactions suggestions, and share their vision for future StretchAR applications.

4.2 Task 1: Stretch-Touch Procedure Description

The first task assesses the influence of body location, the number of fingers, and the level of applied stretch on the accuracy with which the user interacts with an AR target using StretchAR. The target chosen was a horizontal multiple-choice menu (Figure 4a). To complete this task, the user needs to horizontally displace a virtual sphere until it meets a virtual target by pulling the StrechAR. Releasing the StretchAR makes the virtual sphere return to its original position. A central banner displays two messages: The number of fingers that the participant must use to move the source ball (on the left) and the position of the target (on the right). The task measurements start when the participant begins stretching the interactive strap and finish when the strap is released. During this interaction, the amount of stretching applied to StretchAR translates to the horizontal displacement of the virtual sphere. An essential feature of the test was that participants were free to choose how they would hold and pull the StretchAR during the interaction. Additionally, the standing bodies of the users had complete freedom of movement during the task. We collected and explored the variety of interaction methods used to complete the task. At the same time, we mounted StretchAR on different body parts. Figure 4a illustrates the scenario of task 1, where participants wearing a HMD (Hololens 2) could observe three main virtual objects (sphere, banner, and target).

The variables used for task 1 were: i) The body location of the strap (head, chest, forearm, or wrist) that was defined considering the preferred and most common body locations for interactions [79]; ii) the number of fingers (1–3) that participants could use to interact with the StretchAR; iii) the stretching (strain, ϵ) of StretchAR. The target ball was placed at horizontal distances that required stretching the strap at 25%, 50%, 75%, and 100% of their original length. We decided to validate the stretch-touch interaction using different stretch values to confirm the accuracy of StretchAR. Task 1 was repeated by attaching the StretchAR to the head, chest, forearm, and wrist of the participant and requesting to reach each of the four levels of stretching mentioned using one, two, and three fingers. Since each measurement was repeated three times, the number of trials per participant was 144 (4 body locations x3 different fingers x4 levels of stretching x3 repetitions).

4.3 Task 2: Scroll-Touch Procedure Description

Task 2 aims to assess the influence of the four proposed body locations, the number of fingers, and the scroll/swipe direction on the performance and accuracy of the user while using StretchAR to interact with a virtual rotational menu. These types of menus (Figure. 4b) are beneficial to save space on the field of view of the users, reducing the amount of information displayed and lowering the mental load. To complete this task, participants need to rotate the virtual cylindrical menu until a green target bar (source bar) overlaps a red target bar using scroll/swipe interactions enabled by StretchAR. The action ends when the participant stops scrolling, and the source green bar overlaps the red target bar. The participants use scroll/swipe actions on StretchAR to control the direction of the rotational menu. Following a similar approach as the one used in Task 1, a central virtual banner displays the instructions for the participant, the number of fingers required to execute the scroll/swipe interactions, and the direction (Up/Down) for the scrolling/swiping interaction. We also alternated the position of StretchAR across the four body locations (head, chest, forearm, and wrist). We allowed the participants to move while performing the interactions freely. During the user study, we collected the completion time and the variety of methods used by participants to perform this task.

Task 2 uses three variables to evaluate the performance of the participants and the type of interactions employed across: i) Different body location of StretchAR (head, chest, forearm, wrist); ii) the number of fingers (1–3) that participants needed to use to scroll/swipe; iii) the direction of the scroll/swipe interactions (up/down). The location of the red target bar was in front of the participants as shown in (Figure 4b) and was constant during the task. The source green bar position on the cylindrical menu was different for each repetition but constant across participants. We repeated Task 2 by attaching StretchAR over the four proposed body locations of the participant and requested to rotate the cylindrical menu following the virtual banner instructions. Since each measurement was repeated three times, the number of trials per participant was 72 (4 body locations x 3 different fingers x 2 scroll/swipe directions x 3 repetitions). We also used the counterbalancing method during this task.

4.4 Interview — Procedure

At the end of the user study, we conducted a short interview with each participant. The purpose of this interview was to collect new stretch-touch and scroll-touch interaction modalities based on what each participant considered the most intuitive use of StretchAR. We performed the interview after the user study to take advantage of the familiarity of the users with StretchAR-based interactions. We showed the participants a set of indoor and outdoor images such as home automation, hiking, and gaming activities to encourage the discussion of new forms of interaction using StretchAR. Participants were free to choose where to place StretchAR on their bodies and how to perform the interaction. The only requirement was to use StretchAR as a single input modality.

5 RESULTS AND DISCUSSION

5.1 Results from Task 1: Exploration of Stretch-touch Interactions

5.1.1 Task Completion: We performed a three-factorial analysis within-subjects—after the collected data passed Mauchly's test of sphericity–to determine the influence of our three independent variables (body location, number of fingers, and level of stretch) on the performance of the task (using SPSS v.28.0). We used the time of completion of each of the trials in the analysis. Posthoc tests confirmed no statistically significant interaction effects between variables ($p > 0.05$, see Figure 5a).

Specifically, we found that body location ($F_{3,39} = 2.32, p = 0.09$) and stretch level ($F_{3,39} = 0.516$) do not have an statistically significant effect in the performance of the users (Figure 5a). This result demonstrates that StretchAR can be mounted on the head, chest, forearm, and wrist without a decrease in the overall performance of the user. Similarly, using only stretch inputs, participants can move virtual objects independently of the orientation and position of the pulling interaction. On the other hand, the number of fingers used during the interaction

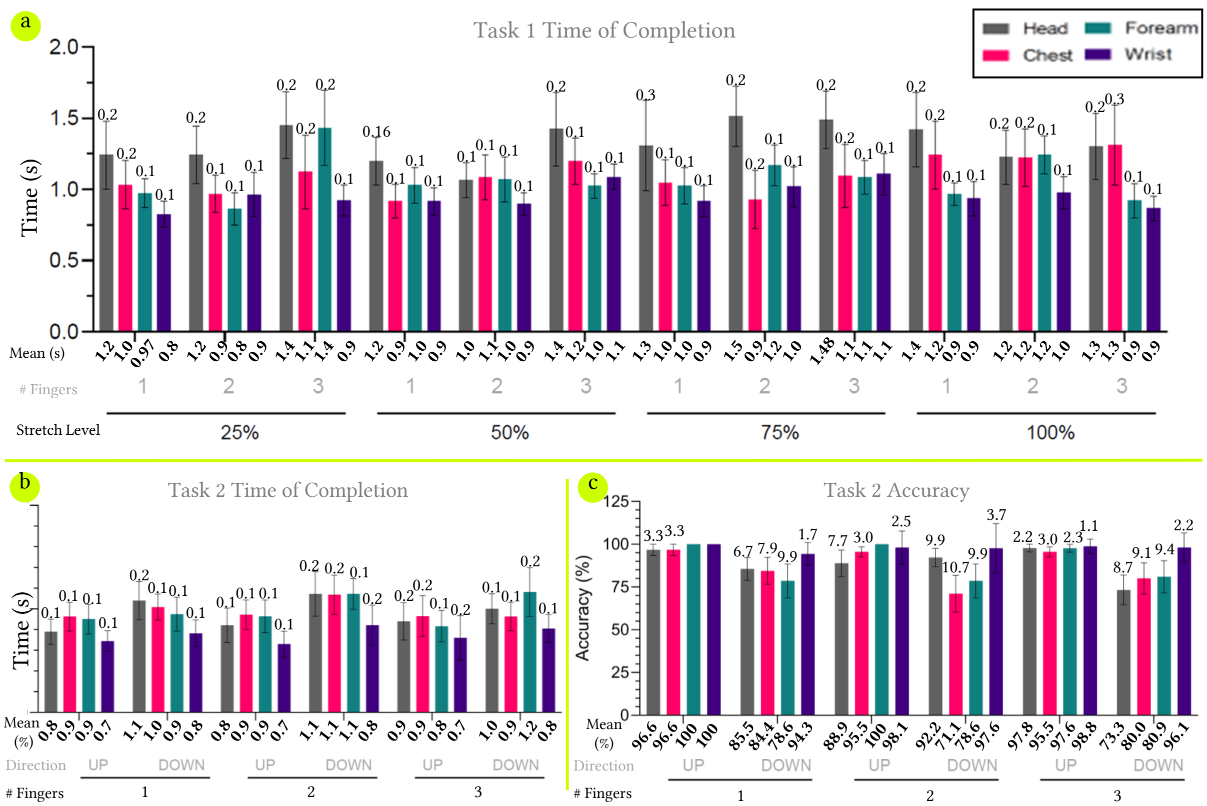

Fig. 5. Evaluation results (mean values and standard error of mean (SEM)) from the user study showing the performance of the participants in terms of: a) Average completion time for Task 1—time and SEM for each body location and finger combinations, b) Average Time of Completion of Task 2—time and SEM for each body location and finger combinations, and c) Accuracy of completion during Task 2.

($F_{2,26} = 3.81$, $p = 0.035$, $\eta^2 = 0.0813$) has a statistically significant effect on the performance of the user. However, this effect on the performance is not large enough to heavily influence the time of the interactions and the overall test outcome. Moreover, since StretchAR distinguishes the same stretch interaction according to the number of fingers (1–3) used to perform the stretching, StretchAR can provide three different interactions using the same stretching action, adding versatility to stretch-touch interactions.

5.1.2 Accuracy: We used the three independent variables (body location, number of fingers, and level of stretch) to determine the effect of these variables on the accuracy of the participants during the stretch-touch interactions. The users perform the stretch-touch tasks with perfect accuracy. We attribute this result to three main factors: i) the calibration of the touch sensitivity for each user; ii) the detection of the number of fingers while holding the strap, which reduced the detection errors; iii) the application of a tolerance of ±2 to the stretch measurements considering the technical evaluation reference and the radius of the target sphere. After enhancing the accuracy of stretch-touch interaction, our results confirm that the use of StretchAR on any part of the body is a suitable alternative method to interact with smart glasses.

5.1.3 Convenience: The evaluation of convenience allows us to identify the most effective way to complete an activity while considering multiple parameters. For this purpose, we ask our participants to evaluate convenience in terms of body location, effort, response speed, personalization, and usability of StretchAR during stretch-touch interactions. We used a 0–10 visual analog Likert scale to quantify the level of convenience. Higher scale values indicate higher level of convenience [38, 76, 86, 89]. Since the data collected was not normally distributed, we used a non-parametric Friedman's ANOVA to analyze the evaluation of convenience. When considering the action of stretching the StretchAR, we found that there is a statistical difference in the perceived convenience of the participants towards the body location during the interaction ($X^2(3) = 13.75, p = 0.003$). We used Kendall's coefficient of concordance analysis ($X^2(3) = 13.75, p = 0.003, W = 0.306$) to confirm—through pair-wise comparisons—that the use of StretchAR on wrists (p=0.01) and the forearm (p=0.005) is considered more convenient than its use on the head during the performance of stretch-touch interactions. No significant effects were observed on the rest of the combinations (p>0.05), which can be explained by the conformability and lightweight of StretchAR to the body of the user.

Since participants require to wear a set of smart glasses or HMDs while performing stretch-touch interactions, there is an obstruction factor for StretchAR on the head. This obstruction becomes evident when, due to the motion of the users, the displacement of the smart glasses partially blocks StretchAR and complicates the performance of hold and pull actions. We believe that when using stretch-touch interactions on the head, it is necessary to ensure that StretchAR is placed over the frame of the smart glasses and that the force necessary for stretch interactions is not enough to pull the smart glasses out of place.

5.2 Results from Task 2: Exploration of Scroll-touch Interactions

5.2.1 Task Completion: To analyze the data collected, we first confirmed that it did not violate Mauchly's test of sphericity and then performed a three-factorial analysis within-subjects. We used three independent variables (body location, number of fingers, and scroll direction) to determine the effect of these variables on the performance of the participants during the time of completion of the scroll-touch interactions (using SPSS v.28.0). We also conducted a Bonferroni corrected pairwise t-test for posthoc analysis. We found that the effect of the body location ($F_{2,24} = 0.009$), scroll direction ($F_{1,12} = 0.38$), and the number of fingers ($F_{2,24} = 1.81, p = 0.185$) were not statistical significant (Figure 5b). Similarly to Task 1, the interactions between variables did not significantly affect the performance of participants ($F < 1, p > 0.05$). Demonstrating that the three variables of this user study do not significantly affect the effective completion of scroll-touch interactions. All the participants were able to complete the assigned tasks without significant difficulty. Furthermore, the scroll-touch interactions used to manipulate a rotational cylindrical menu were successfully completed independently of the location and orientation of the strap, which indicates the familiarity of the users with scroll interactions.

5.2.2 Accuracy: We analyzed the accuracy of the data collected by first ensuring sphericity with Mauchly's test and, then, performing a three-factorial analysis within-subjects. We used the same three independent variables (body location, number of fingers, and scroll direction) to determine the effect of these variables on the accuracy of the participants during the scroll-touch interactions with rotational AR menus (using SPSS v.28.0). We also conducted a Bonferroni corrected pairwise t-test for posthoc analysis. The analysis showed that the number of fingers ($F_{2,26} = 2.299, p = 0.120$) , and the body locations ($F_{2,26} = 0.023$) main effects on the accuracy were not statistically significant (Figure 5c). However, the direction of the scroll/swipe action ($F_{1,13} = 13.49, p = 0.003, r = 0.45$) has a statistically significant effect on the accuracy. We evaluated the results from the posthoc test and found that the interactions between body location x scroll direction ($F_{2,26} = 0.5$), body location x number of fingers ($F_{4,52} = 0.615$), scroll direction x number of fingers ($F_{2,26} = 0.295$) were not statistically significant. However, when the compared interaction included the three conditions: body location, scroll direction, and the number of fingers used, we found a statistically significant influence of the combinations on the accuracy ($F_{4,52} = 2.716, p = 0.04, r = 0.1$). From these results, we can confirm that the body locations and the number of fingers do not significantly affect the accuracy of the participants during scroll-touch interactions with rotational virtual menus and that the effect of the scroll direction can be effectively compensated by the participant so that it does not have a significant effect on the accuracy of the task. Figure 5c shows a drop in accuracy when participants performed the scroll down interaction. We attribute this effect to the combinations of three main factors: i) The method of interaction selected by the users. Users that interacted using the gestures B4, C4 (Figure 7) for the chest, and E4, F4 for the forearm (Figure 7) were the ones that showed the lowest accuracy among the participants. We attribute this low accuracy to the fact that the participants needed to re-map the rotation of the cylindrical menu to the scrolling direction for each body location; ii) The orientation of the fingers while scrolling on the strap. The touch detection principle favors the longitudinal movement of the fingers along the strap. The participants had to orient their fingers parallel to the direction of the strap. However, participants randomly changed the position of their hand during the performance of the task; iii) Participants sometimes missed touching the strap with all their fingers, leading to the incorrect identification of the scroll direction. These factors did not significantly affect the scroll-touch interaction with the wrist because of the natural and well-known body position to perform the interactions.

5.2.3 Convenience: Similar to Task 1 convenience, participants evaluate convenience in terms of body location, effort, response speed, personalization, and usability of StretchAR during the scroll-touch interactions. We used a 0−10 visual analog Likert scale to score the level of convenience. The higher value of the scale indicates a higher level of convenience [38, 76, 86, 89]. Since the data collected was not normally distributed, we used a non-parametric Friedman's ANOVA to analyze the data. We found that the perception of the convenience of the use of StretchAR on different body locations to perform scroll-touch interaction was not statistically significant ($X^2(3) = 0.849, p = 0.838$). While during the analysis of the stretch-touch interactions (Task 1), we found significant differences in the perceived convenience of using StretchAR on the head, wrist, and forearm. These differences were not significant for scroll-touch interactions, as the participants felt that the proposed body locations were all convenient for the performance of scroll-touch inputs. This result demonstrates that participants can easily perform scroll-touch interactions independently of the number of fingers used and the body location of StretchAR.

5.3 StretchAR Subjective Workload and Willingness to Use Analysis

5.3.1 Raw NASA TLX: . We used the Raw NASA task load index (NASA TLX) to indicate the overall workload of each of the body locations in each task [9]. Figure 6a illustrates the scores that participants reported for both stretch-touch and scroll-touch interactions. We observed that the maximum mean score (Raw NASA TLX=30, SD=13.39) was obtained for the head during the examination of the stretch-touch interactions. The minimum mean scores (Raw NASA TLX=20.8) were obtained for the forearm and wrist. Since there were no significant differences between the body locations (p>0.05), we can state that the proposed body locations present a low workload for the participants during Task 1, and none of them was significantly demanding compared to the others.

During the examination of the scroll-touch interactions, the results from the questionnaire showed a significant difference between the scores from the head and the other body locations (Figure 6a). The Raw NASA TLX score for the head was 47.5% (SD = 9.96) during scroll-touch interactions, suggesting that participants felt the scroll-based interactions on the head considerably demanding. Comparing the scores between body locations shows a significant difference between the head with the chest, forearm, and wrist (p<0.0001). This workload difference can be attributed to the short time between each trial during Task 2 since scroll-touch interactions

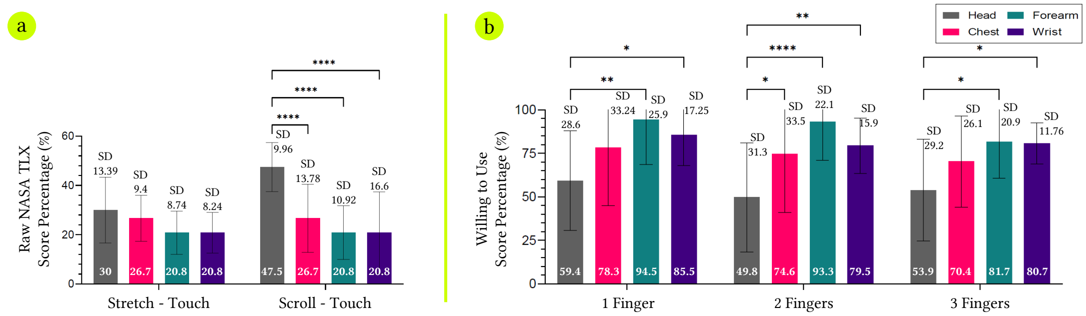

Fig. 6. a) NASA Task Load Index results from the evaluation of StretchAR, b) Participants willingness to use SterchAR for each type of interaction modality.

require shorthand movements for fast interactions. That caused the participants to feel the effort on their shoulders when their arms repeatedly reached their heads.

5.3.2 Willingness to Use: After the test, we asked the participants to rate each combination between body parts and the number of fingers used according to their personal experience. Each participant rated the twelve possible combinations on a 0–100 scale. We used this data to quantify the willingness to use StretchAR. To analyze the data collected, we used a two-way ANOVA within-subjects after satisfying Mauchly's test of sphericity, which indicated that the assumption of sphericity had not been violated for body locations ($X^2(5) = 3.48, p = 0.67$) and a number of fingers ($X^2(2) = 2.92, p = 0.23$). From the data analysis, the test within-subjects revealed that the main effect of body location on the willingness to use of the participants was statistically significant ($F_{3,9} = 19.37, p < 0.01, r = 0.55$). However, the number of fingers used ($F_{2,16} = 1.225, p = 0.358$) and the interaction between body location and number of fingers ($F_{6,18} = 0.65$) were not statistically significant. These results demonstrate that body location was the leading factor when the participants evaluated their willingness to use StretchAR.

5.4 Interviews — Results

From the semi-structured interviews, we collected information from the comments of the users about the interactions, other StretchAR configurations, and wearable applications. Participants suggested different alternatives for interactions during active scenarios like gaming and hiking. For example, in multi-player gaming, participants (9/15) suggested mounting StretchAR on their forearm or wrist to transform wrist motions and arm directions into virtual actions in the game. Participant P4 said, *"use the forearm stretch for shooting, and stretch gesture on the chest or head for changing weapons."* Participant P8 suggested using interactions to shoot in a game using a tap gesture on the head, inspired by a popular comic-book character. He recreated the action and said: *"use tap gesture with two fingers, like a laser beam."* Participant P1 added functionalities such as reloading ammunition with a strap located on the waist. Participants P1 and P8 suggested mounting StretchAR on suspenders so that their stretching would zoom in and out in navigation, hiking, or outdoor environments. Participant P15 wondered *"if the strap could detect the speed we use to do the swipe action to react accordingly and move things faster,"* which would be desirable in scenarios with large amounts of elements such as books, social media, videos, and menus requiring a rapid scan of the information when searching for specific content. In a similar context, the use of the intensity (P15) and duration (P13) of stretch-touch interaction was highlighted to define directionality (P2) and summon other interaction options. Overall, most participants (12/15) used their forearm and wrist to perform StretchAR-based interactions to perform familiar tasks, such as turn on/off, open/close menus, control light intensity, speed, temperature, or volume. The inclusion of other body parts happened when the activities and scenarios required more specific actions, like the case of outdoor hiking and the gaming scenarios, where the participants included chest, head, and waist.

Overall, participants evaluate StretchAR under four body locations and different configurations, allowing them to provide multiple gestures and applications during the interview. From the information obtained during the interview regarding the applications (Table 2), participants demonstrated the versatility of StrechAR. We observed how users could embed interactive straps into clothing and accessories, representing an easy way to adapt to various body shapes, activities, and needs. This adaptability and personalization allow users to use StretchAR in social environments, where conventional interaction methods such as hand gestures [6–8, 52] and controllers [45, 68] are inadequate or uncomfortable. Finally, the eyes-free and adaptable nature of the interactions using StretchAR provides additional affordances for seamless and dynamic interactions. Representing an advantage over other methodologies that require specific patterns [59, 60], or visual attention to interact [4, 5, 44, 57, 58].

5.5 StretchAR Interaction Modalities

Figure 7 shows the groups of StretchAR interaction modalities collected from the user study. The main groups are divided according to body location (Figure 7 a, b, c, d). The main groups are internally divided according to the properties of the gesture (posture, grasping, orientation), stretch, and scroll direction. Additionally, each of the gestures in Figure 7 include the percentage of participants who employed the interaction during the user study for each number of fingers used. We found 28 interaction configurations across participants during Task 1 and Task 2 and labeled them as stretch-touch-based (in yellow) and scroll-touch-based (purple), see Figure 7. Under each interaction modality, we provide the agreement score for each number of fingers ((1),(2),(3)) used to perform the interaction [90].

5.5.1 Variations in the Manipulation of StretchAR: . During the evaluation, all participants were free to decide how to execute the requested StretchAR-based interactions according to their comfort perspective. Participants could choose the hand they wanted to use, the position of StretchAR on the body location, and the grasping method they will use to perform the actions. The agreement scores shown in Figure 7 allows for the rapid identification of the preferred methods of interaction configuration across all participants. The participants switched continuously between these gestures during the evaluation tasks: For example, during the head-stretch task, participants preferred interaction B1 (see Figure 7), where participants stretched the strap by placing the fingers between the head and stretchAR from the top side of the strap. Similarly, during the head-scroll task, participants preferred interaction E1, which uses the fingers to scroll forward and backward perpendicular to the ground. Interaction F1 appeared as an alternative to E1, as the smaller size of the hand of one participant allowed the use of two fingers parallel to the ground to scroll over StretchAR. Most participants preferred to use their dominant hand over the non-dominant side of their body. In the case of the head, however, the interactions were performed only with the dominant hand and on the same side of the head. Some of these configurations and poses helped the participants visualize how to interact in the augmented environment according to their previous experience and cultural background. For example, participant *P8* mentioned during the interview: "I feel like Ironman" while interacting with the holograms displayed into the smart glasses using StretchAR. We found five factors that affected the variability in the manipulation of StretchAR: 1) the participant position (standing, sitting, resting on a table while standing); 2) the orientation/direction of the virtual objects; 3) the morphology of the participants (mainly the chest area); 4) the orientation of StretchAR over the body location; 5) the position of the body location that holds StretchAR. Based on the combination of these factors, the participants opted for those configurations that allow them to interact fast and comfortably with the smart glasses.

5.5.2 Comfort Perception: To understand the perception of the comfort of the users while using StretchAR, we made a convenience inquiry about the use of the different interactions shown in Figure 7. These results showed

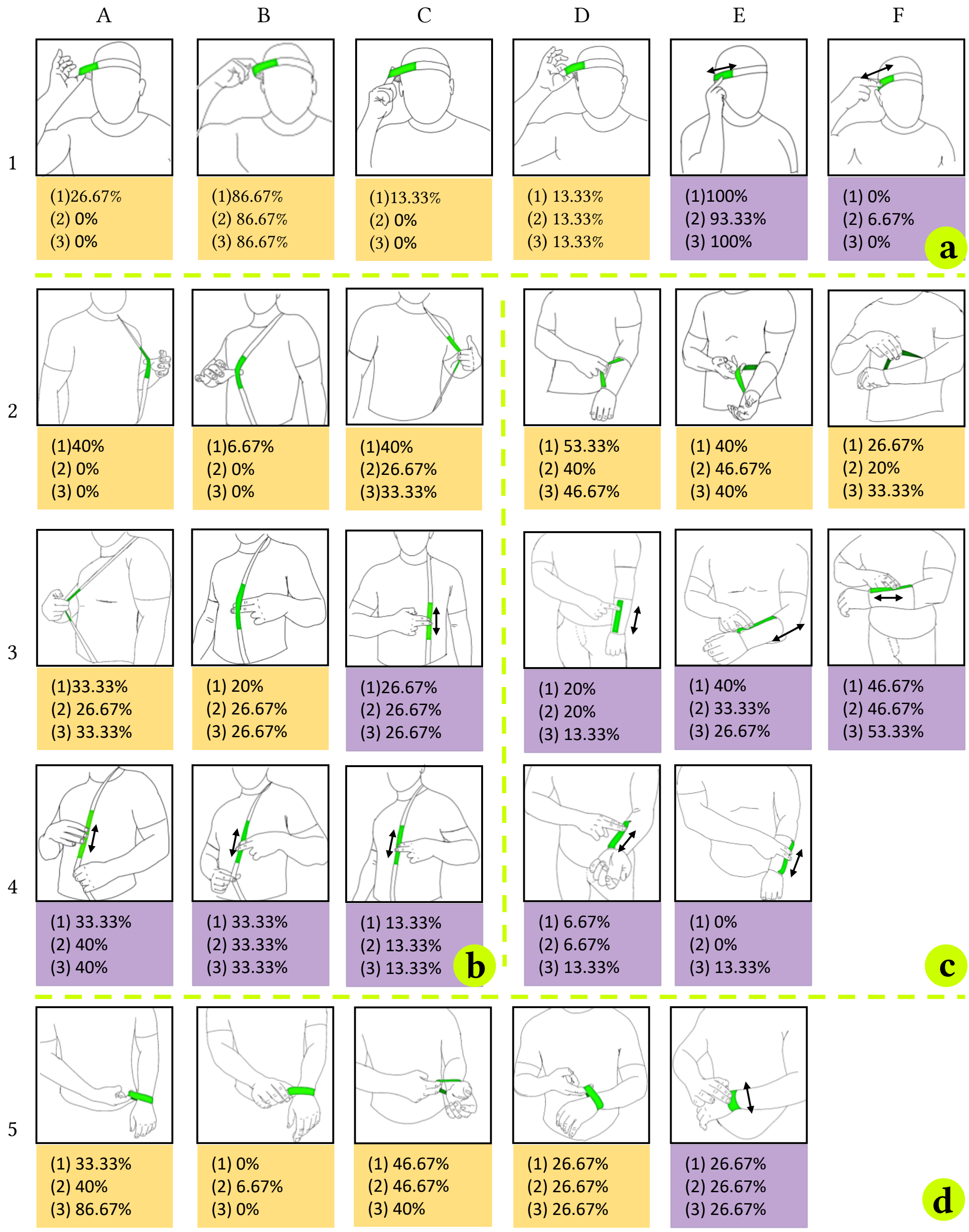

Fig. 7. Frequency distribution of the stretch-touch interactions employed by the participants during the user study. Yellow labels indicate stretch-touch interactions. Purple labels indicate scroll-touch interactions. The numbers (1), (2), and (3) represent the number of fingers used to perform the illustrated interaction. Sections were divided using the main body parts a) head, b) chest, c) forearm, and d) wrist

that participants had a positive perception of the comfort derived from the use of StretchAR for human-AR interactions. The freedom with which participants selected the best way to interact with StretchAR during its evaluation and the agreement scores in Figure 7 can confirm the comfort perceived through the variety of manipulations chosen by the participants. Participants explored multiple interaction alternatives to find the best option for each specific task. For example, interaction C1 in Figure 7 appeared as an evolution of interaction B1, since two of the participants found more convenient to change the position of their elbow while interacting with the smart glasses. A similar effect occurred with D3 and E3, where participants switched the support hand to continue working on the touch-scroll task. The changes made by the participants maintained the same response from the system independent of the way they executed the interaction. Participants found comfort during the interactions despite the multiple repetitive actions required along with the user study. Due to their conformable design and their simple integration onto garments, we envision StretchAR to be perceived as comfortable by those users that require to perform short and fast eyes-free interactions such as zooming in/out, accepting or canceling a call, making emergency calls, interacting with features of IoT devices, scrolling through social media and email content, or even enlarge and shrink virtual objects.

Despite the lack of statistical significance, in terms of convenience across body locations, interaction with the StretchAR mounted on the head required more effort (Fig.6a). Participant *P1* mentioned, "The head is a very natural and convenient method to interact, but it can be exhausting and uncomfortable to use it for long periods". Expanding on that comment, *P11*, said, "it is not hard or complex to use it, but it is uncomfortable because you can pull the smart glasses with it".

The versatility of StretchAR enables the creation of comfortable interactions for the wearer and has the potential to allow more users to access new forms of technology and assist in including smart glasses in the performance of daily activities. While the creation of a universal method of interaction for smart glasses has been hindered by the variety of users, applications, and mobility features that AR provides, StretchAR allows the possibility to use a multimodal interaction technique that adapts to the needs, lifestyle, and general requirements of the user.

6 STRETCHAR INTERACTION-BASED GUIDELINES

Based on the results of the user study of StretchAr, we have elaborated a list of guidelines and implications that will contribute to the fabrication and development of SertchAR-based interactions with smart glasses. We divide the guidelines into two main groups: Manufacturing and Interaction guidelines.

6.1 Manufacturing Guidelines to Ensure intuitive Interactions

6.1.1 Structure and Configuration.

- **Substrate Material:** The main feature to consider when manufacturing StretchAR is the choice of the base substrate. During the fabrication of the StretchAR prototypes used, we mainly focused on maintaining a high degree of conformability while preventing potential short circuits between the functional layers during stretching. When exploring substrates with different tensile strengths, we suggest avoiding using braided and woven elastic bands with high rigidity, as they compromise the conformability of StretchAR and complicate the performance of natural pulling interactions. Additionally, as observed during the user study, the application of excessive pulling forces led to the deformation of the garment supporting StretchAR. This fact allow us to conclude that the comfort and wearability of StretchAR can be compromised by inadequate interaction. While pulling conventional elastic bands, their width reduces, significantly decreasing the touch-sensitive contact and compromising touch and scroll detection. We suggest using soft knitted elastic bands and Fold-Over Elastics for manufacturing StretchAR. These substrates maintain a near-constant width during stretching, even for large strain values.

- **Size and Configuration:** We defined the size of StretchAR according to two correlated factors: a) the hand size of the users, and b) the number of touch-sensitive contact pads. We used the range of standard hand breadth values published at the NASA Human Integration Design Handbook [63] (7.1–10.2 cm). We used the maximum value from this range as the minimum length of StretchAR to ensure all users would be able to fit four of their fingers on the smart strap and have enough space to perform the interactions. Using this convention, the final length of StretchAR was 11 cm, which proved to detect both stretch-touch and scroll-touch interactions successfully. Using the length of the strap, we defined the number of electrodes by dividing the length of the strap into equal sections based on half of the maximum fingertip size (2.5 cm) [63]. We opted for an arrow shape contact pad to cover more space and reduce the number of contact pads. Additionally, these contact pads ensure that every time a user touches the strap, a finger will contact at least two pads (even during stretching). According to the accuracy limitations observed during Task 2, the design of StretchAR could benefit from multidirectional scroll identification. It will enable the detection of the number of fingers independent of the orientation of the fingers and ensure a higher accuracy level. These features will ensure the functionality of StretchAR independent of the length and the number of contact pads needed for the fabricated garment.
- **Materials to Avoid:** We recommend to constraint the material space of StretchAR to materials that allow the sliding of the fingers over the surface without restrictions. Elastomers and rubbers generally exhibit sticky surfaces that constrain continuous smooth motion and complicate their integration with textiles and garments. Additionally, conductive threads should be avoided in the fabrication of the electrodes/touch pads as they rapidly deteriorate with continuous touch interaction.
- **Stretchability Requirement:** We selected an off-the-shelf elastic band with a relatively high stretchability and smooth surfaces as the substrate for StretchAR. However, we can personalize the stretching amount of the substrate according to the preferences of the user and the desired applications. During our user study, participants stretched StretchAR until they completed the tasks. The purpose of the tasks was to test the limits of detection when StretchAR was near the maximum of its linear stretch ($\epsilon \sim 70$), but the stretch levels could have been reduced to complete the same tasks. We observed that some participants perceived the stretching of StretchAR as excessive during the interactions. Therefore, future StretchAR designs could define the range of work for StretchAR, reducing the effort of the user, providing intuitive haptic feedback, and creating even more seamless interactions.
- **Touch Detection:** Participants used many types of grasping and touching gestures to interact with StretchAR. We consider that the touch detection area should be expanded to both sides of the strap, so that the strap will be able to identify any type of gesture used. Additionally, this configuration could provide additional functionalities such as sensitivity to pinch-like gestures.

6.1.2 *Interfacing Garments.*

- **Body Location:** StretchAR can be configured, adapted, and placed on a variety of body locations. The applications and the preference of the user defines the location of this interactive strap. We reported that participants preferred to place StretchAR on the forearm and wrist when the interactions were oriented to everyday actions and repetitive activities. Additionally, our results demonstrated that the use of StretchAR on the head, chest, or wrist has a high level of acceptability when performing more specialized activities such as outdoors and gaming.
- **Interface Method Selection:** We observed considerable pulling effects on the accessories used to hold the strap on the body locations during the evaluation. The force needed to stretch the strap was similar to

those required to pull spandex, so users do not need to make a significant effort to interact with it. Based on these observations, it is crucial to define the method to attach the strap with the body location or garment.

The body location becomes particularly relevant when defining how to interface the strap with other elements. For example, when StretchAR is on the head, the perception of the interaction is not the same as when it is on the forearm or the wrist. To mount StretchAR on the wrist, we sewed a stretchable layer of mechanical adhesive (Velcro) directly on the back surface of the elastic band substrate. This configuration facilitates size adjustments of StretchAR, which is desirable when interacting with users with different body types. Based on our results and the interaction method chosen by each participant (Figure 7), it is critically important to ensure that the strength of the mechanical connection is enough to withstand the pulling forces of the users during the stretch-touch interactions. The direction, force, and body location of the strap define the type of integration. We can suggest three methods to interface StretchAR with garments to support each interaction modality: 1) to directly sew the strap to an existent garment; 2) to embed StretchAR as part of the structure of a garment or accessory; 3) to use metal rings similar to our prototype to allow StretchAR to be easily transferable to different locations.

6.2 Interaction Guidelines

- **Types of Applications:** Applications that require short and fast interactions combined with low levels of attention are best suited to benefit from stretch-touch interactions. The applications illustrated in Section 7 are clear examples of fast interactions that are usually supported by virtual menus, social media interfaces, notifications display, or IoT interactions. From the conversation and interview discussion with the participants, we extracted a list of interactions mentioned repeatedly by the participants that StretchAR can support (Table 2).

Table 2. Interactions compatible for StretchAR

Stretch-Touch	Scroll-Touch	Touch
Enlarge	Scroll up/down	Open
Shrink	Swipe	Close
Zoom in/out	Social Media	Confirm
Move	Increase Volume	Help
Set up camera timer	Decrease Volume	Emergency calls
Increase Volume	Fan speed	Mute
Decrease Volume	Temperature control	Select
Fan speed	Light intensity	Take pictures
Temperature control	Accept Call	Start recording
Light intensity	Reject call	tap
Previous	Previous	continuous taps
Next	Next	long press

- **Additional Capabilities:** We observed how participants tried to align their interactions to the direction of movement during the user studies and interviews. Applications and movement direction add a new level of interaction for StretchAR. Therefore, we suggest considering the dynamics of the augmented scenarios to develop a more intuitive and natural way to interact with virtual content. StretchAR will benefit from additional hardware to perform other functionalities such as inertial measurement units (IMU) or additional stretch sensors.
- **Effort:** The interaction modalities need to be responsive and straightforward to adopt. During the user studies, participants showed some fatigue while executing continuous repetitions of interactions on the

head (Figure 6). To enhance the perception of the users and overall usability of StretchAR, we suggest considering features such as responsiveness and controllability to improve the experience, acceptability, and efficiency of the users while interacting with StretchAR.

- **New Configurations:** A convenient feature of StretchAR is its capability to be combined with other StretchAR to create new forms of interaction. Some participants suggested combining two StretchAR on the forearm as a cross or a T-shape to do a multi-directional scroll (P1, P4, P8) to achieve additional interactions. Similarly, we could fabricate StretchAT with one free end and place it on the chest or the pockets area to add more alternatives for interaction (P1, P9, P15, P13). Additionally, the stretching sensor configuration could be changed to add functionalities. We could divide the stretch sensor into two parts to help determine the direction of the pulling, which would allow the user to move virtual objects up and down using stretching intuitively. Finally, several participants (P1, P2, P3) suggested the enhancement of current passive straps in garments and other accessories by incorporating StretchAR on belts, backpacks, parachutes, guitar straps, shoulder bags, shoulder decorations, and ties.

7 EXAMPLE APPLICATIONS

We selected three activities augmented with virtual content to demonstrate the applicability and versatility of StretchAR using stretch-touch and scroll-touch interactions with smart glasses. We selected outdoors, indoors, and entertainment applications to exhibit the use of the collected interaction configurations extracted from the user studies and interviews.

7.1 Virtual Map Navigation

The combination of stretch and touch provides a great variety of possibilities to interact with virtual content instantly and at any moment. Using P1 comment to use two straps on the chest, we built a map navigation application for hikers and trail runners (Figure 8a). We instrumented a backpack with two interactive StretchAR straps (see Supplementary video). We used it to interface the user with a virtual map displayed using HMDs [2]. We enabled interactions such as zoom-in by pulling both straps with one finger on each strap (C2-Figure 7). The zoom-in interaction stops when the user releases the straps. Similarly, by pulling the strap with two fingers, the users can zoom out the map view (C2-Figure 7). To navigate the map and observe different locations, the user stretches the left strap with two fingers to pan left or stretches the right strap with two fingers to pan right (F3/F2-Figure 7). For moving the map up and down, the user will stretch only one strap at a time using the F2/F3 interaction with two fingers. A left stretch will move the map down, and a right strap stretch will move the map up. Finally, the user double-taps with two fingers over the right strap to select a destination. The interactions enabled the users to locate places or tag locations to visit. We illustrated the versatility and potential of StretchAR by implementing simple interactions executed with a pair of straps for outdoor activities.

7.2 Gaming

Gaming in AR is an arduous task that requires synchronization of the virtual objects among the users and fast dynamic interactions (typically performed with dedicated controllers). Using Pokemon go and HADO [31] as references, we created a virtual shooting game that allows users to interact with a holographic 3D menu and flying drones (Figure 8b). Currently, users require touch screens or mid-air gestures to see and interact with the virtual content. Both scenarios are often considered uncomfortable and unintuitive, which does not allow users to enjoy the full potential that AR gaming can provide. We implemented a shooting game application that receives the commands generated from the interaction with StretchAR (see Supplementary video). We wore StretchAR on the wrist to allow fast and easy access to the interaction requirements of the game. The interaction modality used a two-finger scroll interaction (B4 Figure 7) to move the options of the 3D menu. The menu rotates around

Fig. 8. Application scenarios based on the interviews suggestions that demonstrate some of the potential applications of StretchAR: a) Virtual map navigation, b) Augmented reality Gaming activity, and c) Home automation and assistive environments.

the user and then taps StretchAR to select the weapon. To play, the user will need to use a two-finger pull as shown in A3 Figure 7 to shoot the virtual drones displayed.

7.3 Home Automation: Assistive Environments

Augmenting home objects with voice commands and virtual assistants is rapidly growing in popularity. We present an application to augment an apartment using IoT devices controlled by AR interfaces(Figure 8c). Users could supervise and modify fan speed, light intensity, and temperature by interacting with the interfaces controlled by StretchAR (see Supplementary video). Participants agreed that the forearm and wrist were the preferred body locations for common everyday activities during the user studies. Using StretchAR, users can benefit from stretch-touch and scroll-touch interactions to manipulate the different controllers in the apartment. The user would wear the strap on the wrist and performs the E5 scroll interaction (Figure 7) for light intensity control, a single tap to control on/off actions with a fan, and a two-finger pull (D5 Figure 7) to interact with the temperature controls. The automation of spaces and buildings is helpful to add comfort and to enhance the accessibility for users with disabilities.

8 LIMITATIONS AND FUTURE WORK

8.1 StretchAR Design and Integration

The robust StretchAR prototype presented here (Figure 2) was created with the aim of achieving a high level of accuracy in the quantification of stretch, multifinger-touch, and scrolling across the whole user study, allowing for the exploration of stretch-touch human-AR interactions. There are, however, other requirements that future StretchAR will need to incorporate in their designs to better meet the needs of the users. For example, as a smart textile, the design of StretchAR should consider the incorporation of additional functionalities such as GPS location, acceleration sensors, visual displays, haptic tensions, and customized aesthetics. Additionally, we expect StretchAR to benefit from a completely wireless design, which will allow the rapid attachment and reattachment of the smart strap between different users or body locations with the help of existing stretchable mechanical adhesives. Furthermore, the incorporation of self-powering elements and stretchable electronic circuitry into StretchAR could expand both their autonomy, sensing capabilities, and interaction modes.

8.2 Stretch-Touch Interactions

Combining stretch, touch, and scrolling gestures to perform AR interactions that do not have a direct equivalent in the real world might require high levels of mental load, which could hinder the adoption of StretchAR. StretchAR, however, could be used to intuitively manipulate soft or deformable virtual objects by combining touch and stretch in a similar way as how the user interacts with real objects. As an example, StretchAR will allow the user to better interface with elastic virtual elements, such as bows, pulling cords, dough, or textiles.

8.3 Evaluation

Randomized conditions were applied to all the tasks evaluated, minimizing the effect of repetition on participant's performance. This randomization, however, does not protect against ordering effects. Additionally, considering a 95% confidence level and a 5% margin of error, it would be necessary to evaluate ~300 participants to meet the statistical constraints necessary to reach significance. The study presented, however, meets the StretchAR's evaluation goals (Section 4) and is in line with previous research work [53, 59, 80].

8.4 In-Motion Interactions with Virtual Content

At their current level of development, StretchAR can only be used to evaluate static users in augmented scenarios. Future extensions of StretchAR can exploit stretch-touch interactions while the user is in motion. Therefore, StretchAR-based interactions will become more robust once the effect in sensing performance of walking, running, and other user motions are taken into account. We anticipate that, as smart glasses become lighter, more accessible, and extensively used, there will be a growing need to develop accurate dynamic interactions while the user naturally moves across unstructured environments.

9 CONCLUSION

In summary, StretchAR represents a genre of stretchable smart-straps that enable fast and eyes-free interactions between wearers and their smart glasses using stretch-touch inputs. StretchAR can be mounted on different parts of the body and on a variety of outfits, enabling natural interactions with AR content across users with different body types. The multilayer design of StretchAR and conductive thread allow us to monitor stretch and touch as independent variables. As a result, even during stretching, StretchAR detects the number of fingers in contact with an accuracy of 96% (SD=0.68) and the number of fingers scrolling with an accuracy of 96% (SD=0.81). Through a user study with 15 participants, we demonstrate the potential and viability of StretchAR as a natural input modality to interact with the 3D virtual content displayed by smart glasses. Moreover, our study provides a collection of intuitive interaction gestures and a set of guidelines to exploit the benefits of stretch-touch human-AR interactions and to fabricate StretchAR using scalable manufacturing processes. We envision StretchAR to serve as a cornerstone for the future design of deformable interactive wearables and e-textiles exploiting touch and stretch as intuitive haptic human-AR input modalities.

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