Can We Redesign a Shoulder Exosuit to Enhance Comfort and Usability Without Reducing Assistance?

Roberto Ferroni, Daniele Filippo Mauceri, Jacopo Carpaneto, Alessandra Pedrocchi, *Senior Member, IEEE*, and Tommaso Proietti

***Abstract*— Reduced shoulder mobility limits upper-limb function and daily activities across a wide range of conditions. Wearable exosuits have shown promise in assisting arm movements and reducing muscle effort; however, comfort has rarely been prioritized as an explicit design objective, despite it strongly affects mass-adoption and long-term usage. This study presents a redesigned soft shoulder exosuit developed to address comfort-related limitations identified in our previous version. In parallel, the actuator-harness configuration has been redesigned to bias assistance preferentially toward shoulder flexion, to enhance functionally relevant hand positioning. A comparison between the previous (v1) and redesigned (v2) versions was conducted in eight healthy participants, who performed static, dynamic, and functional tasks, with muscle activity, kinematics, and user-reported feedback as main outcomes. Both versions increased endurance time and reduced deltoid activation when assistance was active, without hindering movement freedom when unpowered. However, the difference emerged most clearly during functional tasks and comfort evaluation. Version 2 was associated with forward-directed arm elevation and larger transverse-plane mobility by up to 30°, without a detected increase in deltoid activation. User-reported outcomes further suggested improved wearability, with lower perceived pressure across the harness and higher ratings in effectiveness (+23%), ease of use (+20%), and comfort (+17%) compared to the previous version. Taken together, these findings suggest that redesign strategies focused on wearability and task-oriented assistance can improve comfort and functional interaction without compromising assistive performance.**

***Index Terms*— Wearable robotics, soft robotics, exoskeleton.**

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I. Introduction

The shoulder plays a central role in upper-limb manipulation and activities of daily living (ADLs). Decreases in shoulder range of motion (ROM) impedes the capacity to perform ADLs, which can occur at all ages, as a consequence of a broad variety of conditions or injuries, such as stroke, spinal cord injury, or amyotrophic lateral sclerosis [1]. These conditions markedly affect autonomy and social participation, while increasing healthcare costs and caregiver burden [2], [3].

In the last three decades a large body of research in rehabilitation and assistive robotics aimed at mitigating upper-limb movement deficits. This common effort resulted in the creation of multiple exoskeletons, whether rigid or soft actuated, achieving promising results in a variety of applications [4], [5]. However, while the field has evolved, a common challenge to any wearable architecture, perhaps the most overlooked, remained comfort. Despite it has often being declared as a design goal, comfort is rarely central to the design process and to the outcomes of a study. For rigid robots, a few studies proposed mechanisms to adapt the exoskeleton's kinematics to the user [8], [9], but this remains critical due to limitations in structural adjustability [10]. For soft exosuits, comfort is often assumed to be an inherent property [6], [7], and metrics related to user experience are reported less systematically than performance outcomes and mostly via questionnaires [12], [13], [14]. Besides qualitative tools, more quantitative and interface-focused works exist. These included systematically measuring regional force and pressure limits at the body–device interface to map comfort boundaries [11], [21] and their dependence on use and loading dynamics [22]; optimizing how assistive forces are routed and distributed across multiple anchoring points using human–robot models and structural design methods to reduce local interaction forces [23]; and adopting broader evaluation frameworks that couple power transmission metrics with additional interface phenomena such as compression, shear, slippage, and perceived comfort to better capture overall human–exosuit interaction quality [24], [25].

Yet, while more acceptable in short-term applications, comfort-related issues continue to be acknowledged as critical for wearability and long-term use [16], [17]. For instance, commonly reported limitations include textile slippage, pressure-related discomfort, actuation perturbations due to muscle volume variability, and joint misalignment during motion [15]. Comfort becomes even more critical when the device is intended for individuals with motor impairments, for whom comfort, stability, and the ability to adjust the system to individual needs and daily variability are essential for safe and sustained use [18], [19]. A key challenge in addressing comfort is that improving wearability may lead to reduced generated torque [20] and thus exoskeleton's performance.

Building on this context, the present study moves from our previous shoulder exosuit design (v1), whose efficacy has been extensively demonstrated through studies on both healthy and impaired participants [26], [27], [28], toward a new design to address identified limitations–including comfort–by making them explicit requirement of this new version (v2). Beyond comfort optimization, the redesigned system biased the resultant assistance preferentially toward shoulder flexion, while maintaining multi-planar mobility. In contrast, the v1 primarily supported shoulder abduction in the coronal plane. This redesign reflects the functional relevance of forward-directed arm elevation for ADLs (*e.g.*, personal care, feeding), where effective hand positioning in the frontal workspace is primarily achieved by shoulder flexion rather than abduction.

Regarding comfort, the study combined (1) objective measures, including mechanical transparency during arm elevation (in either the sagittal or coronal plane) as well as in the transverse plane to assess possible movement restrictions in shoulder horizontal adduction, with (2) qualitative user feedback, including satisfaction, perceived pressure intensity, and perceived direction of shoulder motion during assistance. To enable a controlled comparison between versions, we evaluated both systems in a cohort of eight healthy participants, naïve to either version of the device, across multiple experimental tasks, including static, dynamic, and functional activities, with identical tasks and conditions applied to both versions.

II. Materials and Methods

A. Soft Shoulder Version 1

The robot v1 has been previously described in detail, both as a standalone device and in combination with other upper-limb assistance modules [26], [27], [28], [29]. It features a fabric-based pneumatic actuator coupled to the body through a custom shoulder brace and Velcro straps to ensure stable fitting on the torso and arm, see Fig. 1. Upon inflation, the actuator tends to straighten. With the lower portion constrained at the torso interface, the expansion produces an upward and lateral lifting action about the shoulder joint, primarily oriented toward the frontal plane, and resulting predominantly in shoulder abduction.

B. Soft Shoulder Version 2

The redesigned exosuit was conceived to reproduce the mechanical interaction exploited in the previous version while reorienting the assistance toward the sagittal plane to primarily support shoulder flexion, see Fig. 1. Moreover, trunk compression due to the inflation of the actuator has been often described as the main source of discomfort, especially by healthy users. To this end, both the anchoring configuration and the direction of actuator expansion were redefined to generate a forward and upward assistive force aligned with the desired movement, without relying on the torso as a lateral anatomical constraint. The new architecture introduces a set of coordinated mechanical constraints to maintain the generated torque and to stabilize and guide the actuator deformation during inflation. Specifically, the actuator is laterally aligned along the torso via a zipper interface integrated into the harness, while 3D printed arm cuffs provide proximal and distal anchoring to the upper arm. Crucially, an inferior mechanical constraint is introduced through a belt-and-buckle system connecting the lower end of the actuator to the thoracic harness. This inferior anchoring stabilizes the actuator's base, allowing pressurization to generate a controlled forward and upward displacement of the upper section. The anchoring interface consists of a belt-like waist vest designed to couple the actuator to the body while maintaining comfort and adaptability to different body sizes. The harness features a hybrid textile construction that combines a 3 mm thick 3D spacer mesh for breathability, with a high-strength non-stretch fabric providing structural support (Supplementary Fig. S1). The main structure comprises a rectangular thoracic band (22.3×111.5 cm) secured around the torso using two primary Velcro straps. Two additional pairs of Velcro straps tension the non-stretch textile components and allow side-by-side or overlapping configurations to accommodate different torso sizes. For improved comfort, two body-facing fabric pockets house a 1 mm thick flexible thermoplastic plate to distribute contact pressure, thereby mitigating localized pressure concentrations. A representative demonstration of the v2 assistive motion is available in Supplementary Video S1. Both versions of the pneumatic actuators were manually controlled to a pressure setpoint using an external control unit. Actuator pressure was regulated through a closed-loop bang-bang controller with hysteresis. Additional details on the pneumatic control unit, pressure regulation strategy, and controller limitations are provided in the Supplementary Materials and Fig. S2.

C. Study Design

To compare the two robots, we carried experiments with eight healthy individuals in a single session, using both versions of the robot in a randomized order (4 males; inclusion criteria: 18-65 years old, able to lift a 4-kg weight with their dominant hand, and no record of major upper-limb injuries; see Supplementary Table S1 for participant demographics). Informed consent was obtained prior to participation. Data collection took place at the Biorobotics Institute of Scuola Superiore Sant'Anna, after approval of the testing protocol (01/2024) by the Joint Ethics Committee of the Scuola Normale Superiore and the Scuola Superiore Sant'Anna.

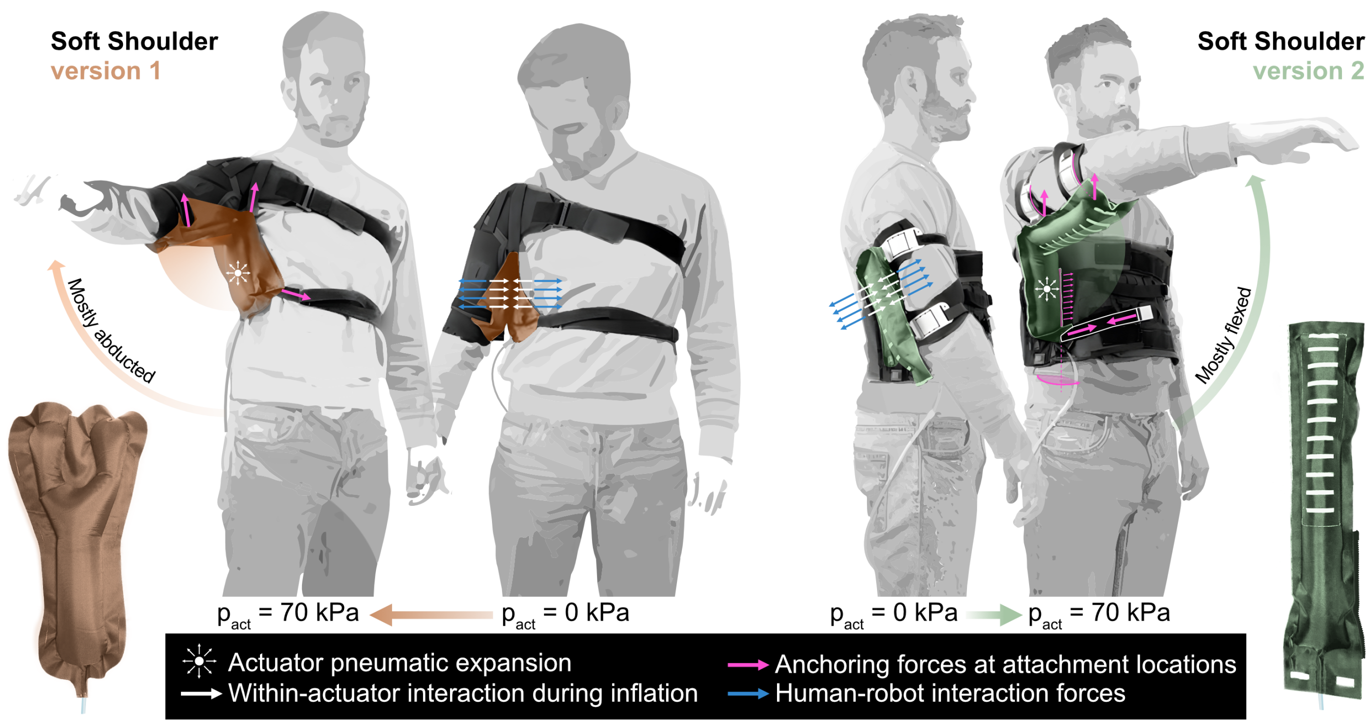

Fig. 1. **Comparison of the shoulder exosuits v1 (orange) and v2 (green).** Each actuator consisted of a fabric-based inflatable air chamber and is shown both alone and worn on a user. Force diagrams show the working principle: as pressure increases, the two portions spanning the armpit (anchored to the arm and the torso) begin to press against each other (white arrows), generating the initial driving force for the movement (blue arrows). As inflation progresses, the actuator stiffens and approaches its straight configuration, resulting in an upward motion of the arm through the attachments that secure the actuator's mobile portion to the upper arm. The anchoring forces at the attachment locations (purple arrows) are crucial for establishing a stable interaction with the body and ensuring that the intended primary direction of motion is consistently elicited (*i.e.*, shoulder abduction for v1 and shoulder flexion for v2).

To assess and compare robotic support, surface electromyographic (EMG) activity was recorded using wet electrodes (Sessantaquattro+, OT Bioelettronica) from the anterior (AD), middle (MD), and posterior (PD) heads of the deltoid muscle. Electrode placement followed standard recommendations [30]. To enable inter-subject comparisons, maximum voluntary contraction (MVC) was recorded for each EMG channel at the beginning of each session. MVC was computed as the mean of the maximum EMG values obtained from three consecutive isometric contractions. Upper-limb kinematics were also measured using three IMUs placed on sternum, upper arm, and forearm, following standard calibration routine. All trials were video-recorded using a camera (Hero10, GoPro) for reference during data processing.

D. Experimental Protocol

Every participant tested both versions of the shoulder exosuit (v1, v2), either unpowered (robot OFF) or providing assistance (robot ON); to assess mechanical transparency, they also performed movements without wearing any robotic device, as a baseline (NO robot). The experimental protocol, lasting approximately 1 h per device, is shown in Fig. 2, while representative demonstrations of the tested activities are available in Supplementary Video S2. The experimental protocol included two types of measures: (1) user-reported evaluations on comfort, perceived assistance, and satisfaction; and (2) functional assessments, with quantitative measures of the exosuits' performance in supporting physical exercises. Both exosuits and assistive conditions (OFF, ON) were randomized across participants and activities. This testing framework was structured to progress from controlled posture maintenance to ADL-related reaching and finally to a goal-oriented object manipulation task, allowing the assessment of the exosuits across multiple movement directions and functional workspace regions. Information on post-processing and statistical analysis are available in Supplementary Materials.

1) User-Reported Comfort and Perceived Direction of Assistance: To evaluate user experience in terms of comfort and perceived direction of assistance, a passive mobilization of the arm was performed through a full inflation-venting cycle. Each participant was instructed to maintain a relaxed standing posture and avoid actively contributing to the movement. Immediately after this first interaction with the robot, a diagram of the upper body was shown, and participants were asked to: (1) identify any perceived pressure spots by marking the corresponding areas on the diagram; (2) rate the intensity of each pressure sensation ("no pressure", "light pressure", "uncomfortable", "painful"); and (3) indicate the perceived primary direction of arm motion during assistance ("front", "side", "oblique"). Participant-reported pressure maps were then converted into weighted scores based on the marked area and perceived intensity level, as further detailed in the Supplementary Materials.

2) Static Assistance: Participants performed a static maintenance task while holding a load corresponding to 2.5% of their body mass, in two different postures: (1) shoulder abduction

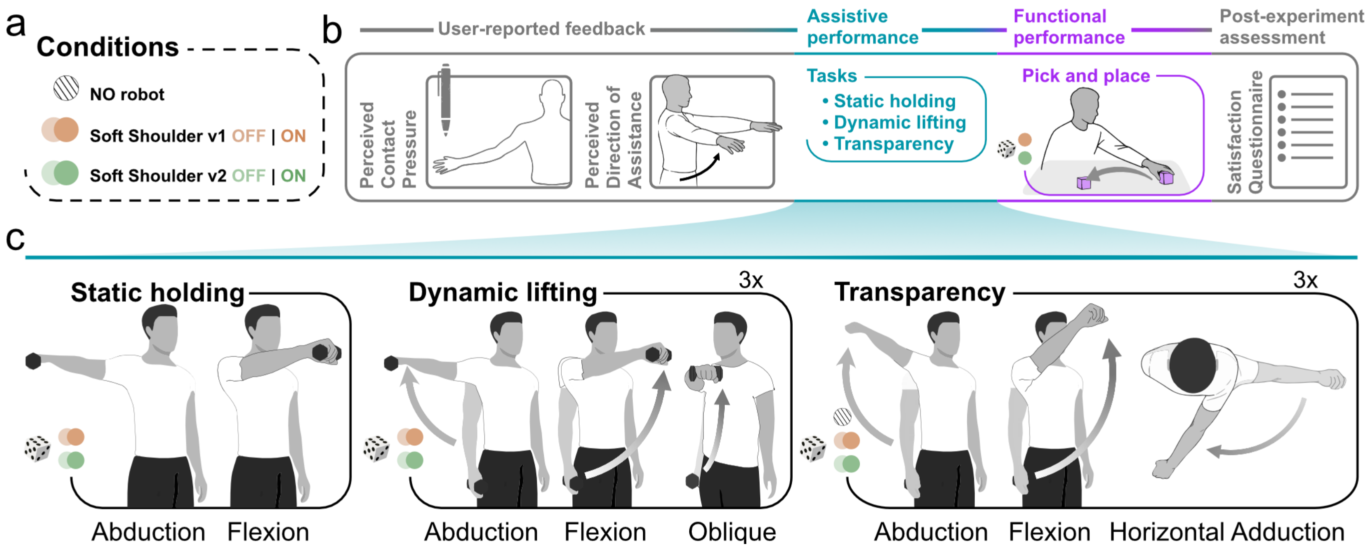

Fig. 2. **Experimental protocol.** (a) Color coded experimental conditions, used throughout the paper: NO robot (no device worn), and the two versions tested in OFF (unpowered) and ON (powered) modes. (b)-(c) Testing session main phases: user-reported feedback; assistive performance (three motor tasks, across multiple directions: static holding, dynamic lifting, and mechanical transparency); functional performance; and final assessment. In each block, tested conditions were randomized across participants.

and (2) shoulder flexion, both to 90 degrees of elevation. A 3-minute rest period was provided between repetitions. Each trial terminated after 10 minutes or when one of the following conditions was met: (1) participant voluntarily stopped due to fatigue; (2) shoulder elevation angle decreased by more than 10 degrees. Endurance time was used as the primary outcome measure, while muscle activity assessed and compare robotic support across exosuit versions and conditions.

3) Dynamic Assistance: Participants performed controlled lifting tasks of a load corresponding to 2.5% of their body mass, following a predefined trajectory displayed on a screen to standardize pacing. Each repetition consisted of three phases: (1) a 7 s lifting phase, during which the arm was raised from rest to 90° of elevation; (2) a 2 s hold phase at the target angle; and (3) a 7 s lowering phase returning to the initial position. The relatively slow movement speed was intentionally adopted to standardize execution and to reflect the slow movement patterns expected in individuals with motor impairments, the intended target population. Movements were performed along three directions: (1) shoulder abduction, (2) shoulder flexion, and (3) contralateral diagonal lift, moving the hand from the ipsilateral hip toward the contralateral shoulder. For each movement direction, the dynamic task was repeated three times under both OFF and ON conditions for each version. A 2-minute rest period was provided between repetitions, and muscle activity was recorded as the primary outcome measure for this exercise.

4) Mechanical Transparency Assessment: The previous version of the exosuit has been shown to be mechanically transparent during shoulder elevation, meaning that it does not restrict free movement when worn unpowered [26]. To assess whether the newer version preserved transparency, participants were instructed to perform isolated shoulder movements along three directions from a rest pose: (1) maximum abduction, (2) maximum flexion, and (3) maximum horizontal adduction, rotating the arm from the ipsilateral to the contralateral side in the horizontal plane. While not directly assisted by the exosuit, the latter movement was assessed as it is functionally relevant for multiplanar shoulder movements and cross-body reaching. Since a soft exosuit should remain compliant to motion beyond primary assisted DOF, this isolated task allowed us to compare whether the two actuator-interface configurations restricted the available transverse-plane workspace. For shoulder abduction and flexion, movements were performed under three conditions: NO robot, v1 OFF, and v2 OFF. For shoulder horizontal adduction, movements were performed under NO robot with external arm-weight support, v1 ON, and v2 ON, as this task required continuous arm-weight compensation. For each shoulder movement and condition, participants completed three consecutive repetitions. Shoulder EMGand sEMG data were recorded and compared across conditions.

5) Functional Pick and Place Task: To evaluate upper-limb movement during a functional, goal-oriented task, participants performed a repetitive pick and place activity, inspired by the box-and-block-test, while seated at a desk. The task required moving as many wooden cubic blocks (2.5 cm side length) as possible from a starting area to a target area, both defined by tape-marked squares on the table surface, while clearing a rectangular obstacle (15 cm in height) positioned between them. The starting area was located on the ipsilateral side of the arm wearing the exosuit, at 45° lateral to the participant's torso, whereas the target area was positioned toward the contralateral shoulder at 45° in the opposite direction. Each trial was performed with both exosuits providing assistance (v1 ON, v2 ON), in a randomized order. As the task primarily involved rotation of the arm in the horizontal plane, IMU data were recorded to assess torso and arm ROMs as primary outcomes while sEMG was collected to quantify robotic support.

6) Post-Experiment User Satisfaction: At the end of the experimental session, participants completed the first 8 items of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST), concerning size, weight, adjustability,

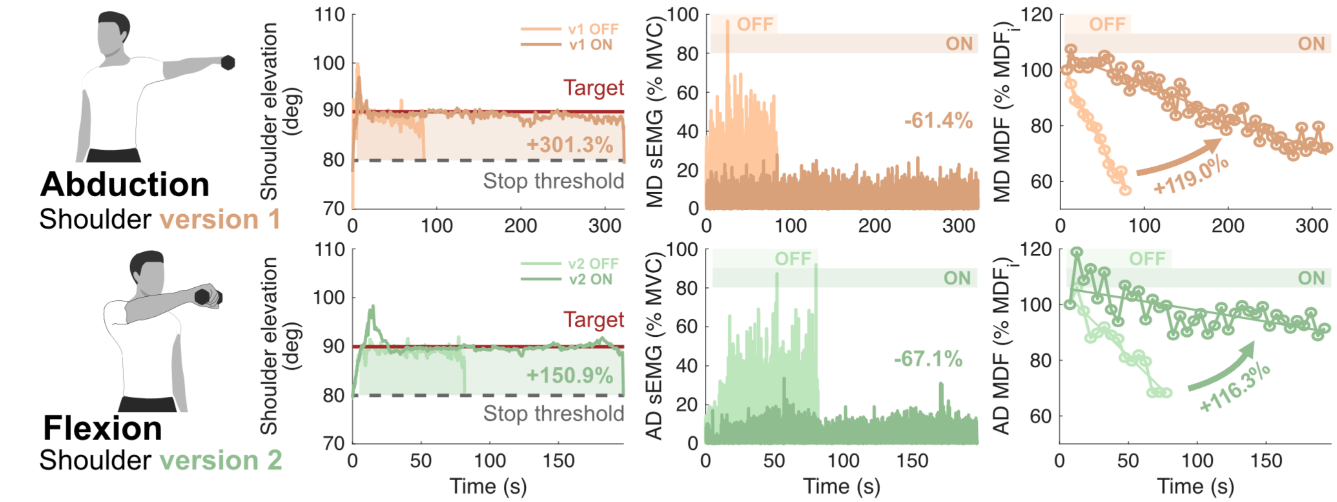

Fig. 3. **Static holding performance across the two design-specific conditions** Representative time-series from a single participant (S6) during sustained static holding tasks. From left to right, shoulder elevation angle, normaliEMGsEMG activity, and its median frequency (MDF) are shown for the primary assisted movement of each exosuit. Exosuit v1 in orange, v2 in green, each shown in unassisted (robot OFF) and assisted (robot ON) conditions. Across both movements, assisted conditions are associated with longer endurance, reduced muscle activation, and a slower decline in MDF.

safety, durability, ease of use, comfort, and effectiveness with a 5-point scale. The remaining QUEST items concerning service-related aspects, were not assessed as not relevant.

III. Results

A. Both Exosuits Are Effective in Their Target Movements

Fig. 3 shows the results of the static exercise for both exosuits, tested in their design-specific movement (shoulder abduction for v1, shoulder flexion for v2). Representative time-series are provided from an exemplary participant (S6), comparing unassisted and assisted conditions. In assisted conditions, the endurance time increased, muscle activation was reduced, and the temporal evolution of fatigue-related indices (EMG median frequency, MDF) appeared to be slower. Table I instead provides a group-level overview of endurance tEMG normalized sEMG activity, and MDF_{Δ} as a proxy for muscle fatigue. Both exosuit versions consistently enhanced participants' performance in their respective movement planes. During shoulder abduction, v1 increased endurance time by 26.6 s, accompanied by a significant reduction in MD activation (median Δ: −7.3%). Similarly, during shoulder flexion, v2 increased endurance time by 61.9 s and reduced AD and MD activations by −4.7% and −3.1%, respectively. Regarding muscle fatigue, MDF_{Δ} values showed a consistent trend towards less negative slopes in the assisted condition ($\Delta > 0$), suggesting a slower shift towards lower frequencies. The interpretation of v1 and v2 as predominantly abduction- and flexion-oriented systems, respectively, is also supported by the supplementary passive assistance-direction tests based on IMU-reconstructed elbow trajectories (Supplementary Fig. S3).

B. Comparable Static Task Performance Across Versions

Endurance time and deltoid muscle activity were analyzed separately for each exosuit version by comparing ON and OFF conditions using paired non-parametric tests, see Table I. Importantly, no participant reached the 10-minute ceiling in any static holding trial. To directly compare the effectiveness of the two versions, subject-specific changes between ON and OFF conditions (Δ = ON − OFF) were computed and compared between versions.

During abduction, both exosuits significantly increased task duration compared to their respective OFF conditions (median Δv1: +26.6 s; median Δv2: +50.9 s). Although the increase was larger for v2, the difference in improvement between versions (Δv1 vs Δv2) did not reach statistical significance ($p_{FDR} > 0.05$).

A similar pattern was observed for deltoid muscle activity. For the MD, the primary muscle involved in shoulder abduction, both versions significantly reduced activation relative to their OFF conditions (median Δv1: −7.3%; median Δv2: −6.6%), with no significant difference between versions. In contrast, a significant reduction in AD activity was observed only with v2 (median Δ: −5.7%), whereas v1 did not yield significant changes for this muscle. No significant effects were detected for the PD in either condition, and the between-version comparison of Δ values did not reveal significant differences. Similarly, during flexion both versions significantly increased task duration relative to their respective OFF condition (median Δv1: +20.5 s; median Δv2: +61.9 s), with no significant difference between the two versions when comparing Δ values.

Regarding muscle activation, both versionEMGgnificantly reduced sEMG activity compared to their respective OFF conditions, although with a muscle-specific pattern. In particular, v1 significantly reduced activation across all three deltoid heads (AD, MD, and PD), whereas v2 showed significant reductions in AD and MD only. No significant differences were observed between versions when comparing the magnitude of change. For the PD, although a statistically significant reduction was observed with v1, overall activation levels remained low across all conditions (median $PD_{v1\ OFF} = 5.4\%$; median $PD_{v2\ OFF} = 5.5\%$; median $PD_{v1\ ON} = 2.5\%$; median

TABLE I
STATIC AND DYNAMIC TASK OUTCOMES. DATA ARE REPORTED AS MEDIAN [Q1–Q3]. ΔV1 AND ΔV2 REPRESENT THE MEDIAN OF SUBJECT-SPECIFIC DIFFERENCES (ON – OFF). P-VALUES ARE BENJAMINI–HOCHBERG FDR-CORRECTED. SIGNIFICANT COMPARISONS (p_{FDR} < 0.05) ARE SHOWN IN BOLD

	v1			v2			Δv1 vs Δv2		
Static - Abduction	**OFF**	**ON**	$\mathbf{p}_{FDR}$	**OFF**	**ON**	$\mathbf{p}_{FDR}$	Δ**v1**	Δ**v2**	$\mathbf{p}_{FDR}$
Time (s)	55.3 [28.0–73.9]	68.3 [54.6–95.6]	**0.033** (*)	53.5 [43.4–62.9]	105.9 [85.3–137.0]	**0.033** (*)	26.6 [13.9–30.6]	50.9 [32.0–76.8]	0.536
AD (%MVC)	10.3 [5.8–17.3]	8.8 [6.8–10.8]	0.312	13.6 [7.7–15.7]	6.1 [4.6–9.0]	**0.033** (*)	-3.5 [-6.6–1.1]	-5.7 [-8.4– -1.6]	0.316
MD (%MVC)	13.9 [9.2–19.6]	5.8 [4.1–9.8]	**0.033** (*)	14.5 [9.0–17.1]	7.3 [4.4–8.4]	**0.033** (*)	-7.3 [-9.9– -6.1]	-6.6 [-8.4– -5.0]	0.760
PD (%MVC)	8.1 [6.1–9.8]	6.2 [2.5–7.8]	0.094	6.1 [4.0–7.5]	2.4 [2.1–3.2]	0.055	-3.0 [-4.3– -1.1]	-3.8 [-4.6– -1.9]	0.760
AD MDF_Δ (%)	-7.7 [-9.4–1.6]	1.4 [-7.6–11.5]	0.255	-8.8 [-26.1– -4.0]	-8.5 [-11.9– -2.3]	0.760	11.1 [-2.1–12.7]	0.9 [-5.4–15.6]	1.000
MD MDF_Δ (%)	-9.3 [-18.7– -5.7]	-9.6 [-14.7– -2.0]	0.718	-9.9 [-27.2– -7.1]	-4.4 [-9.4– -0.7]	0.255	0.8 [-1.7–19.2]	7.7 [2.2–15.8]	0.316
PD MDF_Δ (%)	-2.7 [-7.9–0.7]	-0.6 [-4.6–4.6]	0.779	-0.6 [-8.7–3.2]	-6.9 [-12.3– -4.2]	0.316	1.6 [-3.7–11.1]	-2.8 [-10.5–0.1]	0.375
Static - Flexion									
Time (s)	48.0 [43.7–68.3]	64.3 [61.5–106.7]	**0.047** (*)	50.1 [34.3–70.4]	118.3 [62.8–161.4]	**0.041** (*)	20.5 [11.5–36.6]	61.9 [26.3–90.4]	0.164
AD (%MVC)	13.3 [8.0–17.4]	5.0 [4.4–8.6]	**0.041** (*)	12.1 [7.3–17.4]	9.4 [4.4–9.8]	**0.047** (*)	-5.7 [-8.7– -2.9]	-4.7 [-7.8– -0.9]	0.164
MD (%MVC)	8.2 [5.3–13.6]	3.4 [2.5–5.5]	**0.041** (*)	8.5 [3.6–13.5]	4.8 [3.0–5.9]	**0.041** (*)	-3.6 [-8.6– -1.9]	-3.1 [-5.3– -1.1]	0.536
PD (%MVC)	5.4 [3.0–7.2]	2.5 [1.2–4.2]	**0.047** (*)	5.5 [2.4–6.0]	1.8 [1.8–3.9]	0.445	-2.0 [-3.3– -1.4]	-1.2 [-2.6– -0.4]	0.759
AD MDF_Δ (%)	-6.3 [-10.5– -4.6]	-2.4 [-8.1–4.0]	0.240	-12.0 [-25.6– -2.0]	-8.3 [-9.2– -0.8]	0.191	5.2 [-1.0–10.9]	7.6 [-2.2–11.8]	0.993
MD MDF_Δ (%)	-5.4 [-9.4– -3.6]	0.1 [-3.9–3.8]	0.144	-9.7 [-19.3– -4.9]	-7.1 [-10.7– -1.3]	0.191	7.4 [3.0–10.9]	5.7 [-0.4–13.6]	0.933
PD MDF_Δ (%)	-3.0 [-6.3– -0.2]	-2.7 [-8.6–3.0]	1.000	-8.7 [-13.1– -0.3]	0.5 [-10.4–5.3]	0.866	0.3 [-7.7–10.2]	8.1 [-5.9–11.9]	0.866
Dynamic - Abduction									
AD (%MVC)	10.2 [7.0–13.2]	9.5 [6.6–11.2]	0.176	8.2 [5.6–12.1]	6.3 [4.2–9.0]	0.191	-0.7 [-3.2– -0.1]	-1.0 [-4.2–0.2]	0.431
MD (%MVC)	12.4 [8.6–21.6]	8.2 [4.3–15.5]	0.053	9.5 [8.1–16.3]	6.0 [4.1–11.2]	0.053	-4.0 [-6.4– -0.6]	-3.5 [-5.0– -1.2]	0.547
PD (%MVC)	7.1 [5.3–8.3]	4.7 [3.7–6.3]	0.053	4.9 [2.8–8.0]	3.2 [2.5–6.3]	0.053	-2.5 [-3.0– -1.0]	-1.2 [-2.3– -0.5]	0.176
Dynamic - Flexion									
AD (%MVC)	14.5 [8.4–17.0]	9.3 [7.3–11.6]	**0.023** (*)	9.9 [6.6–13.1]	6.4 [5.1–10.8]	**0.023** (*)	-1.8 [-6.8– -1.2]	-1.9 [-4.5– -1.1]	0.835
MD (%MVC)	8.7 [4.1–12.5]	5.7 [3.0–9.8]	0.450	7.1 [5.2–13.3]	4.2 [2.6–6.2]	**0.023** (*)	-1.3 [-6.8– -0.3]	-2.3 [-6.0– -1.0]	0.945
PD (%MVC)	4.6 [3.0–6.1]	5.0 [2.3–6.7]	0.824	3.9 [1.5–6.9]	3.0 [1.1–4.8]	**0.035** (*)	-0.2 [-0.7–0.5]	-0.9 [-1.3– -0.4]	0.691
Dynamic - Oblique									
AD (%MVC)	12.0 [8.0–18.6]	8.5 [6.9–11.9]	0.267	8.7 [6.5–15.3]	6.3 [4.7–11.6]	0.070	-3.9 [-8.1–0.5]	-3.5 [-4.4– -0.5]	0.844
MD (%MVC)	4.0 [2.2–12.2]	2.8 [2.0–4.1]	0.234	3.1 [2.6–7.3]	2.1 [1.7–3.6]	0.070	-1.2 [-8.0– -0.1]	-1.0 [-1.4– -0.5]	0.603
PD (%MVC)	4.7 [2.8–6.4]	5.0 [2.4–6.4]	0.615	3.6 [1.7–6.4]	2.8 [1.5–6.5]	0.267	-0.2 [-1.2–0.5]	-0.3 [-0.8– -0.2]	0.603

$PD_{v2\ ON}$ = 1.8%), suggesting a limited involvement of this muscle in the task.

These results are consistent with our estimate of gravity-equivalent shoulder torque supported by each version under quasi-static assumptions available in Supplementary Fig. S4.

C. Dynamic Lifting Confirms Flexion Assistance in v2

During shoulder abduction (Table I), although no statistically significant effects were observed, both versions showed a consistent tendency toward reduced deltoid activation, particularly in the MD, the primary muscle involved in this movement. Median MD activity decreased from robot OFF values of 12.4% MVC to 8.2% MVC with v1, and from 9.5% MVC to 6.0% MVC with v2. In v2 ON, shoulder azimuth deviation was 9.1° [0.4–11.8°], and did not differ from 0°, suggesting no detectable systematic anterior deviation (Supplementary Fig. S6). During shoulder flexion, a muscle-specific pattern emerged. Both versions significantly reduced AD activation compared to their respective unassisted conditions (median Δv1: −1.8%; median Δv2: −1.9%). In contrast, significant reductions in MD and PD activity were observed only with v2 (MD median Δ: −2.3%; PD median Δ: −0.9%), whereas v1 did not yield significant changes for these muscles. No significant differences were observed between versions. During the oblique lifting task, which required a coordinated contribution of multiple shoulder muscles, no significant ON − OFF effects were detected. Interestingly, differences were already evident in the OFF condition, with generally lower activation levels observed in the v2 OFF condition compared with v1 OFF across the deltoid heads. This suggests that the harness-actuator of the two versions may have influenced muscle recruitment even in the unpowered state, potentially underlying lower mechanical transparency for the v1 for this specific movement and it is consistent with with the intended flexion-oriented redesign of v2

D. Preserved Elevation With Greater Horizontal Mobility

For movements involving shoulder elevation (abduction and flexion), both exosuits allowed participants to reach physiologically relevant ROMs when worn unpowered. As shown in Fig. 4a, participants consistently achieved shoulder elevation angles exceeding normative functional ROM [31] using either version. In line with this observation, no statistically significant increase in AD, MD, or PD activation was detected compared to the NO robot baseline (Fig. 4b). Thus, neither version introduced clear restrictions to shoulder elevation movements.

In contrast, differences emerged during shoulder horizontal adduction, a DOF not actively assisted by either exosuit but crucial for ADLs. A significant effect was observed on the shoulder azimuth angle (Friedman tests: $\chi^2(2)$ = 12.0,

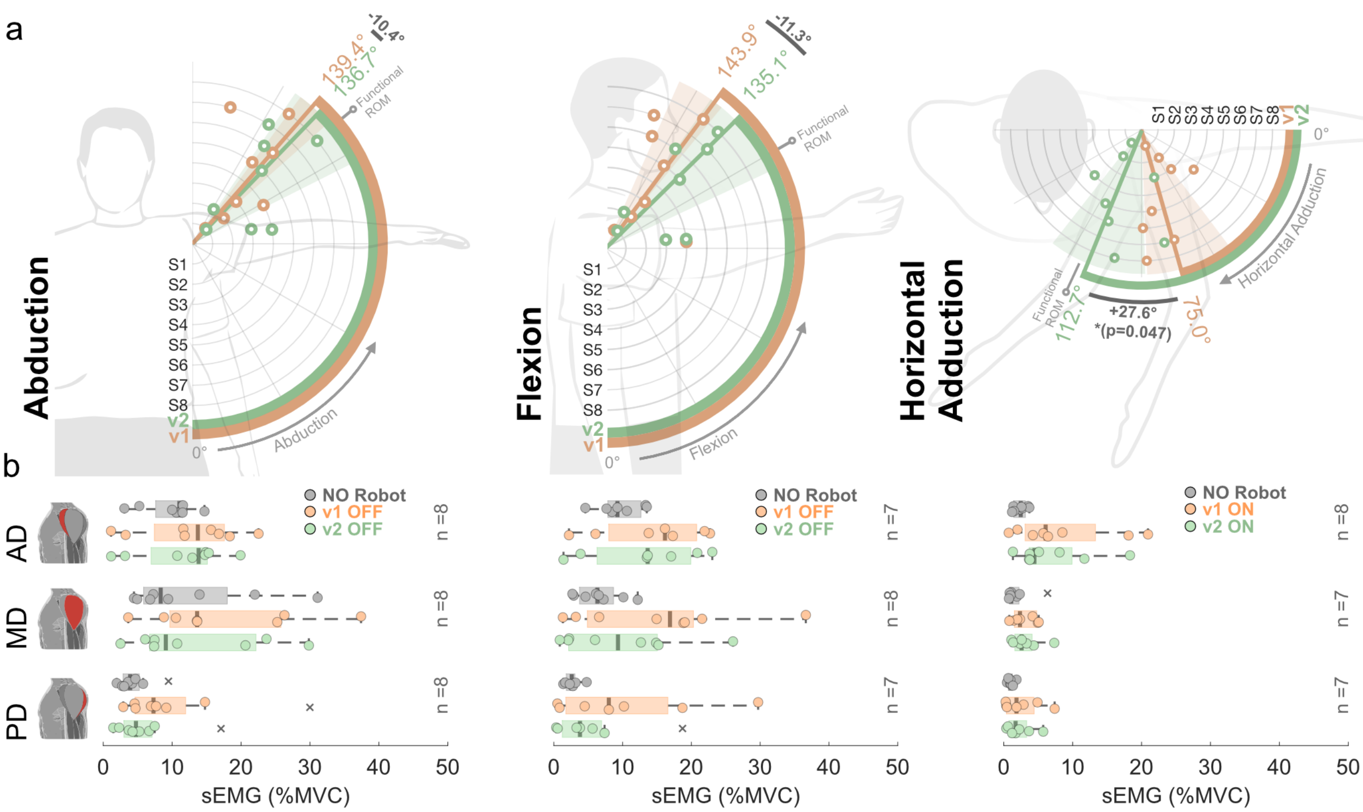

Fig. 4. **Mechanical transparency during isolated shoulder movements.** (a) Shoulder ROM during abduction, flexion, and horizontal adduction movements. Grey lines show normative functional ROMs [31] for reference. During shoulder elevation movements (abduction and flexion), both unpowered exosuits allowed participants to reach physiologically relevant ROMs. During horizontal adduction, v2 allowed a wider shoulder azimuth ROM comparedEMGv1. (b) Boxplots show normalized sEMG activity (%MVC) of AD, MD, and PD heads for each movement direction. No significant increase in deltoid activation was detected relative to the corresponding reference under the tested conditions.

$p = 0.003$). Wearing v1 significantly reduced the achievable shoulder azimuth angle compared to the normative ROM (median Δ: −40.0°, 95% CI −62.0° to −27.3°, $p_{FDR} = 0.047$), and direct comparison between the two versions confirmed a substantially larger ROM with v2 than v1 (median Δ: +27.6°, 95% CI 14.2° to 65.9°, $p_{FDR} = 0.047$). Reference values for shoulder horizontal adduction and transverse-plane shoulder motion during ADLs are summarized in the Supplementary Materials. Importantly, these kinematic differences were not accompanied by increased deltoid muscle activation, as no significant effects of robotic EMGion were detected for AD, MD, or PD sEMG activity (Friedman tests, all $p > 0.05$), suggesting that the larger ROM was not accompanied by a detectable increase in deltoid activation.

E. Preserved Performance With Less Compensatory Movements

During pick and place (Fig. 5), both exosuits enabled comparable functional performance, yielding a similar number of blocks transferred within the one-minute interval (median [IQR]: v1 ON = 21.5 [19–24.5], v2 ON = 19.5 [18–22.5]). Although the overall performance was comparable, differences emerged in movement strategies between the two versions. When using v2, participants exhibited a larger shoulder azimuth ROM (median sAZ: v1 ON = 87.0°, v2 ON = 102.8°) and a reduced elbow flexion angle compared to v1 (median eFE: v1 ON = 49.6°, v2 ON = 39.3°), suggesting increased horizontal shoulder involvement and reduced reliance on more distal joints during object transfer. Importantly, v2 was associated with a significantly lower torso torsion angle than v1 (median Δ: −9.9°, 95% CI −16.8° to −3.6°, $p_{FDR} = 0.047$), indicating reduced engagement of compensatory trunk movements. Reference values for shoulder, elbow, and trunk motion during ADLs, together with previous evidence on compensatory trunk involvement during upper-limb tasks, are summarized in the Supplementary Materials to contextualize these kinematic differences. Moreover, anterior deltoid activation remained comparable between the two versions, despite the observed kinematic differences.

F. Exosuit v2 Improves Comfort and Perceived Interaction

User-reported comfort evaluation revealed clear differences between the two exosuits. Group-level weighted pressure maps (Fig. 6a, 6b) showed a reduced overall contact area for v2, together with a shift toward lower perceived pressure intensity, particularly in sensitive regions such as the armpit and flank. An exception was observed at the upper arm region, which exhibited the smallest reduction in contact surface and a slight increase in weighted pressure score; however, this change remained modest (from 0.25 to 0.38) and well below the level associated with uncomfortable sensations.

QUEST scores consistently improved from v1 to v2 (Fig. 6c). When considering the whole group,

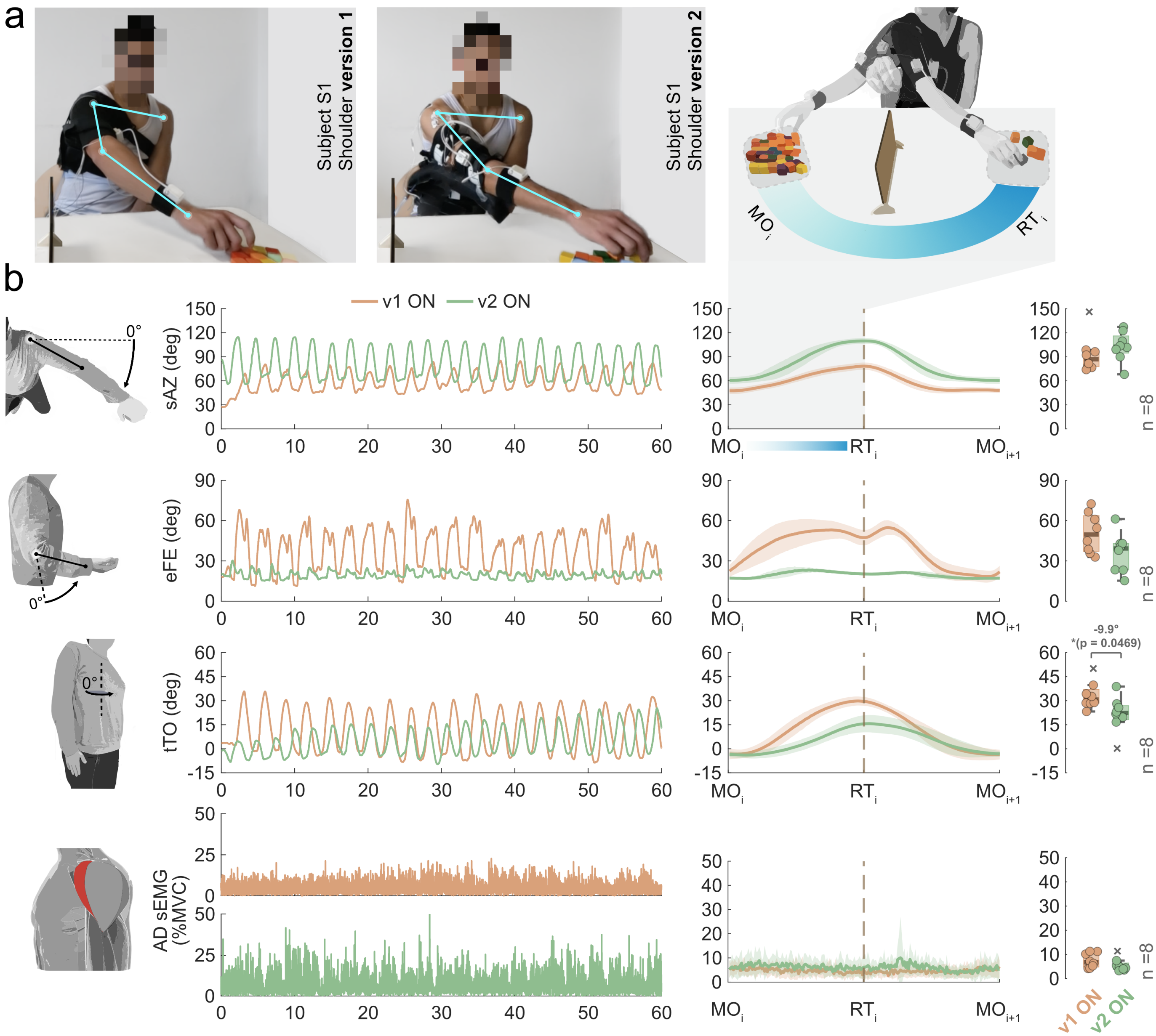

Fig. 5. **Functional pick and place task highlights improved movement strategy.** (a) Representative photographs of a participant performing the task with exosuit v1 (left) and v2 (right). Compared to v1, v2 is associated with increased horizontal arm excursion, reduced elbow flexion, and decreased torso torsion during object transfer. (b) Kinematic and muscle activity data recorded during the pick and place task. Left: representative time-series from one participant (S1) showing shoulder azimuth (sAZ), elbow flex-extensionEMGE), torso torsion (tTO), and normalized sEMG activity of the AD head during task execution with v1ON and v2 ON. Center: same signals, time-normalized and overlaid across repetitions, aligned from movement onset (MO) to release time (RT) and subsequent movement onset. Right:EMGup-level boxplots summarizing kinematic and sEMG outcomes across participants. Notably, v2 is associated with a kinematic strategy characterized by greater shoulder involvement and reduced torso torsion.

participants reported higher satisfaction (for v2, relative to v1) regarding ease of use (+20%), comfort (+17%), and perceived effectiveness (+23%). Absolute QUEST scores for both versions are reported in Supplementary Table S2. Ratings related to weight and durability remained largely unchanged: the former likely reflecting an already well-accepted lightweight design typical of soft robotic systems; the latter representing a qualitative impression that would require longer-term and real-world use to be more thoroughly assessed. An exploratory inspection of relative changes by sex (n= 4 males, n= 4 females) revealed broadly consistent trends for key usability-related dimensions. Both males and females reported improvements in ease of use (M: +17%, F: +23%), comfort (M: +17%, F: +17%), and safety (M: +12%, F: +15%) suggesting that the redesign enhanced perceived wearability across participants. For other characteristics, some preliminary differences emerged: perceived effectiveness was larger in females (M: +16%, F: +29%), whereas adjustments showed opposite trends (M: +18%, F: −6%). Finally, perceived dimensions increased in females (+15%) but decreased in males (−5%), while weight remained unchanged in both groups (0%).

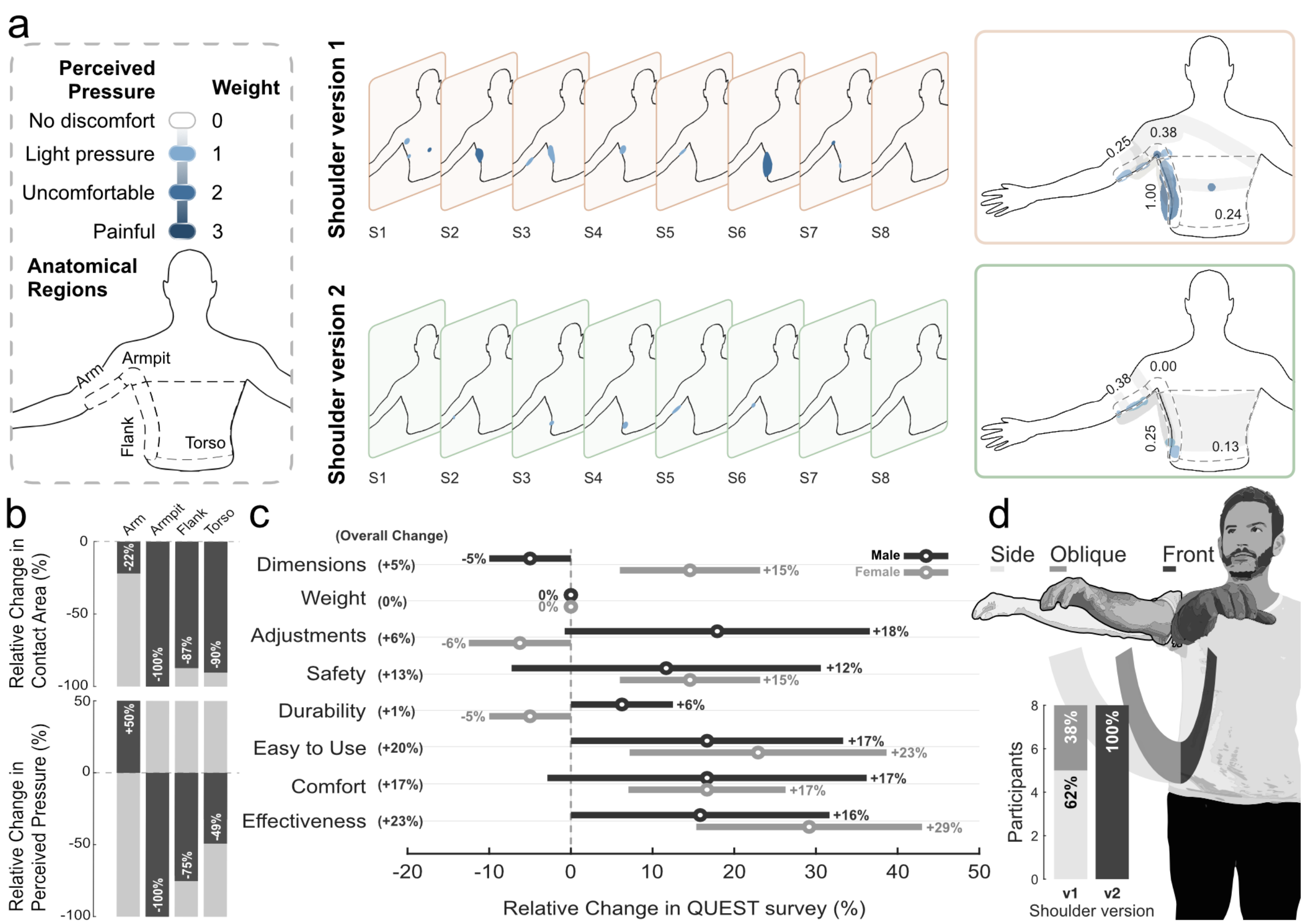

Fig. 6. **User-reported comfort and perceived interaction.** (a) Left: perceived pressure levels levels and anatomical regions on the torso template. Center: individual maps of perceived contact pressure for each exosuit. Right: group-level average weighted intensity maps, highlighting differences in contact area and pressure distribution. (b) Local changes in contact area and perceived pressure intensity across anatomical regions (negative values indicate reduced pressure in v2 relative to v1), indicating an overall reduction in high-intensity pressure with v2. (c) Relative variation (v2-v1) in post-experiment QUEST scores (mean ± SEM) between exosuits, across all participants (pooled sample). v2 was associated with higher ratings in ease of use, comfort, and perceived effectiveness. Sex-stratified values are reported only as exploratory descriptive information, given the small subgroup sizes. Absolute QUEST scores for both versions are provided in Supplementary Table S2. (d) Perceived primary direction of assistance reported by participants, showing a shift toward frontal assistance with v2, consistent with its redesign requirements.

Regarding perceived direction of assistance, participants predominantly identified v2 as providing frontal assistance, whereas v1 was more frequently associated with lateral or oblique support. This perceptual shift is consistent with the redesigned anchoring and sagittal plane-oriented assistance strategy of the updated robot. Supplementary Video S1 shows representative footage of v2 in action across multiple participants, demonstrating the assistive passive movement generated by the device.

IV. Discussion

In this study, we introduced a redesigned shoulder exosuit as an evolution of the previous version, aiming to improve both comfort and the direction of assistance. Compared with v1, v2 incorporates a revised actuator with a new placement, and a novel anchoring architecture to shift the preferential support from a predominantly abductive action toward shoulder flexion. We therefore compared the performance of v2 against v1 to verify whether the redesign met the requirements while preserving the assistive behavior already demonstrated by the earlier prototype. This comparison was not trivial, since v1 had already shown promising results in both healthy and impaired users [26], [27], [28], despite the comfort-related and functional limitations that motivated the redesign.

Across all tasks, the two versions showed strong similarities in core performance: both versions provided measurable signficant assistance during most of the tested movements. In particular, during static holding exercises both designs increased endurance time and reduced muscle activation. During dynamic lifting, both robots complemented muscular effort across movements, with effects aligned with each version's target plane of motion (v1 along abduction, v2 along flexion). Transparency tests suggested that v2, similarly to v1, did not introduce clear restrictions to shoulder elevation when unpowered.

While interpreting these findings, it is useful to distinguish results that confirm the intended design change from those that are more informative about preservation of function and interaction quality. The reduced deltoid activation observed during forward arm positioning with v2 is consistent with the intended flexion-oriented redesign. Instead, preserving support in other direction of movement and without introducing restrictions to shoulder mobility is highly relevant as everyday functional tasks rely on coordinated multi-joint movements rather than isolated DOFs, and often require substantial elbow flexion to effectively position the hand within the workspace. [1]. This is likely due to the soft, body-worn nature of the system, allowing assistance to be preferential rather than geometrically constrained to a single anatomical plane. The direction of the resultant assistance indeed depends on actuator geometry, placement, anchoring, and harness configuration, as well as on current donning.

Importantly, v2 better preserved horizontal-plane mobility, allowing larger shoulder azimuth ranges than v1 without a detected increase in deltoid activation. Additional differences between the two versions became most evident during functional tasks. In the pick and place activity, both exosuits enabled comparable task performance, but v2 promoted a distinct movement strategy characterized by increased shoulder joint excursion, reduced elbow flexion, and significantly lower torso torsion. The latter indicates reduced reliance on compensatory motor behavior, which is potentially crucial as commonly observed in impaired populations (e.g., stroke [32]), and it is inline with the larger available azimuth range.

The new version introduced changes in both the harness and the actuator. The contribution of each redesign element is therefore complex to isolate. However, the comfort-related improvements are more likely the result of the revised harness, anchoring, and pressure-distribution strategy, whereas the functional and directional outcomes reflect the combined effect of actuator orientation, anchoring, and interface mechanics. To clarify this interplay, supplementary tests quantified the effect of harness-only and complete unpowered-exosuit conditions on movement trajectories and muscle activity (Supplementary Fig. S5). However, a more controlled factorial testing would be required to fully disentangle the effects of interface ergonomics and assistance direction. Furthermore, the underlying actuation technology closely matches that of the previous design, for which comprehensive mechanical analyses have already been reported [26], [27].

Consistent with the primary objective of this study, user-reported outcomes suggested improved perceived wearability. Weighted pressure maps revealed an overall reduction in contact area and a shift toward lower perceived pressure intensity. The purposeful local stiffening of the contact interface, particularly on the flank through a thermoplastic rigid plate, likely helped generating a more uniform distribution of contact forces over a larger effective area, with participants thus reporting lower perceived pressure in this region. Although a modest increase in perceived pressure was observed at the arm, this remained well below discomfort levels. Notably, four out of eight participants (1 male, 3 females) reported uncomfortable sensations when using v1, whereas no participant reported discomfort with v2. Post-experiment satisfaction scores further suggested improved perceived usability with v2, particularly for ease of use, comfort, and perceived effectiveness. Ratings related to weight and durability remained largely unchanged; the former likely reflects an already favorable perception of lightweight soft robotic systems, whereas the latter would likely require longer-term and real-world use for proper assessment. An exploratory inspection of the responses by sex (due to small subgroup size; n= 4 males, n= 4 females) showed a slight decrease in perceived adjustability observed by the female participants, which may be consistent with the use of a single-size configuration that, despite being adjustable through straps and attachment interfaces, may have been still large for participants with smaller anthropometric characteristics. Importantly, however, this did not translate into reduced perceived comfort, which increased in both subgroups. Conversely, the greater increase in perceived effectiveness reported by females may partly relate to differences in average body mass between subgroups (M: 75.9 $\pm$ 4.9 kg; F: 53.5 $\pm$ 3.4 kg), potentially influencing the relative perception of assistance.

Future iterations should confirm these results on a larger cohort and likely further improve personalization through multiple harness sizes and actuator configurations tailored to different anthropometric profiles, in line with recent calls within the field [12], while also considering the potential impact of the vest architecture on donning/doffing and wheelchair compatibility in clinical populations.

This study was designed as a preliminary but multidimensional comparative evaluation. Given the small sample size, conservative non-parametric statistics were adopted, and the analysis focused on relative differences between versions rather than absolute performance metrics. Overall, both versions showed consistent trends toward reduced muscle activation and improved performance across tasks. However, these trends did not systematically reach statistical significance, likely reflecting the limited sample size and the relatively low baseline activations observed in these tasks, typically lower than 15% MVC. Moreover, although non-disabled participants provided a controlled setting to compare the two designs, the results will need confirmation with the end-users with impaired motor control, altered muscle tone, increased fatigue, compensatory strategies, and potentially reduced sensory feedback. Clinical validation in the intended target populations will therefore be required.

EMG recordings were limited to the deltoids, thus potentially leaving out compensatory strategies or redistribution of effort across other muscles. To partially address this limitation, supplementary tests included additional EMG recordings from the upper trapezius, pectoralis major, and serratus anterior, providing further insight into passive assistance and transparency-related muscle activity. However, future studies should extend this broader EMG set to the full participant cohort and functional tasks to better assess effort redistribution, scapulothoracic coordination, and compensatory mechanisms. The pressure maps analysis was also limited as they could not quantify absolute contact pressure, localized pressure peaks, or dynamic interface effects (e.g., shear, slippage, interface instability).

From a robustness standpoint, the same actuators sustained approximately 240 inflation-deflation cycles during the experimental and supplementary testing campaign without visible damage, air leakage, or loss of functionality. However, the present study did not include a dedicated long-term wearability assessment or an extended cyclic durability evaluation of the pneumatic actuators and textile interfaces. Although comfort and usability were assessed after sessions lasting approximately one hour per device, future studies should investigate prolonged use, durability, and potential changes in user perception over time.

Overall, these results suggest that targeted, user feedback-driven design refinements may contribute to improvements in functional behavior and comfort while preserving assistive performance. The exploratory comparison of satisfaction across male and female participants also points to the relevance of considering inclusivity and user variability in the evaluation of wearable assistive devices. Ensuring that assistive technologies are not inadvertently biased and that their design appropriately accounts for differences in perception, fit, and usability is essential for equitable deployment [33].

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