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Embodied Intelligent Robots

Cam-Contour-Engineered Passive Shoulder Exoskeleton: Delivering Adjustable Assistance with Minimal Movement Interference

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Abstract: Overhead tasks in industrial and maintenance settings expose workers to prolonged, non-neutral shoulder postures and therefore increase the risk of work-related musculoskeletal disorders (WMSDs). This paper presents the design and experimental evaluation of a passive upper-limb exoskeleton for overhead work. The design addresses two limitations of conventional passive devices: resistance during non-assistive movements and limited adjustability of the assistance level. It incorporates two mechanisms, namely, a Cam-based Variable Torque Mechanism (CVTM) and a Ratchet-based Pretension Adjustment Mechanism (RPAM). The CVTM provides a piecewise torque characteristic. During natural movements (Phase 1), it permits arm motion with low resistance; during overhead work (Phase 2), it generates a programmable torque that varies with arm elevation. The transition between the two phases is determined by a critical elevation angle. The RPAM allows the wearer to adjust the assistance level in discrete steps through cyclic arm movements without external tools. It uses two pawls and a ratchet to change the pretension of the spring. The two mechanisms are integrated into a lightweight carbon-fiber frame. Experimental results show that the exoskeleton reduces shoulder muscle activity and improves postural stability during the tested overhead task.

Keywords: Upper-limb exoskeleton; Passive assistance; Overhead tasks; Variable torque mechanism; Adjustable pretension

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1 Introduction

Overhead tasks that require elevated or otherwise non-neutral shoulder postures are common in aircraft ground maintenance, assembly, construction, and other maintenance operations[1,2,3]. Such tasks are associated with an increased risk of work-related musculoskeletal disorders (WMSDs)[4,5]. Workers may have to hold tools or materials above shoulder height for extended periods, and large shoulder anteversion angles further increase joint loading[3]. Although many industrial operations have been automated, complex activities performed in confined spaces still require human dexterity[6]. Upper-limb exoskeletons have therefore been investigated as an

ergonomic intervention for reducing the biomechanical demands of overhead work[7,8,9].

Upper-limb exoskeletons can be broadly classified as active, semi-active, or passive systems[2,10]. Active systems generate adjustable assistive torque through actuators and control algorithms[11,12]. However, actuators, power sources, and control units generally increase system mass, bulk, and implementation complexity[13]. Semi-active systems use low-power motors to adjust the torque profile and can be more compact and energy-efficient than fully active systems[10,14]. Their manufacturing and maintenance costs, however, may still limit adoption[15]. Passive systems instead use mechanism geometry and elastic elements to produce a prescribed torque profile, allowing relatively lightweight and compact designs [16,17,18,19,20,21,22,23]. Commercial examples include the Skelex 360[24], Ottobock Shoulder[25], and CDYS-S2[26]. These devices demonstrate the benefits of passive assistance, including low mass and reduced system complexity. Nevertheless, their assistance profiles are generally intended for static holding or load support and are not optimized dynamically for different tasks.

Because passive exoskeletons cannot vary their output as freely as active systems, accommodating the diversity of industrial tasks remains challenging. Overhead operations span a wide range of shoulder elevation angles, including screwing in automobile manufacturing[8,27,28], squeeze riveting and sealing in aircraft production[29,30], welding in shipbuilding[2], and order picking in logistics[31]. These operations therefore call for different torque profiles, often with a nonlinear dependence on joint angle, to compensate for gravitational loading effectively[9,14]. The optimal profile also depends on the user. For the same task, individuals with different body dimensions may work at different target angles and require different assistance levels[32]. The required torque can also change when the external load changes, for example, when a worker switches from manual positioning to holding a heavy riveting tool. Passive systems consequently require careful mechanism design so that the delivered torque matches the task and user requirements. For overhead work, an exoskeleton should provide adjustable assistance in the working posture while introducing little resistance during non-assistive movements.

For example, Nasr et al.[33] developed a model-based framework for analyzing optimal assistive torque profiles and optimizing passive mechanism parameters for specific tasks. Tian et al. [15] showed that different overhead tasks require different torque profiles and proposed a torque generator with an adjustable angle of peak assistance to improve task and user adaptability. Their generator switches between low- and high-assistance phases through a passive clutch, thereby reducing interference with natural movements. Zhu et al.[34] presented a variable-stiffness torque generator that produces adjustable torque curves for industrial applications. Ding et al.[1] developed a spring-cam torque generator to match the nonlinear torque demand of the shoulder and demonstrated horizontal translation of the assistive torque curve.

In this paper, we propose a passive upper-limb exoskeleton for overhead work. The system integrates a compact spherical-revolute-revolute (S-R-R) support structure, a cam-based torque-generation mechanism, and an adjustable pretension module. The design treats the assistive torque profile as an explicit design objective so that assistance can be tailored to the task while interference with natural arm motion is limited. We evaluate the system experimentally using muscle activity, postural stability, and metabolic measurements.

This paper is organized as follows. Section 2 introduces the mechanical structure of the exoskeleton and explains its torque generation mechanism. Section 3 describes the experimental protocol for evaluating wearability, and Section 4 reports the experimental results. Finally, Sections 5 and 6 provide a discussion of the findings and concluding remarks.

2 Mechanical Design

2.1 Design Considerations

From a biomechanical perspective, the human shoulder is a complex joint system comprising the sternoclavicular (SC), acromioclavicular (AC), and glenohumeral (GH) joints, together with coupled scapular motion, as shown in Fig. 1a. Shoulder movement therefore cannot be represented accurately by a single spherical joint. For the purpose of exoskeleton design, however, we approximated the shoulder complex by three principal rotational degrees of freedom, as shown in Fig. 1b.

This biomechanical behavior imposes several requirements on a passive assistive device. First, because the biomechanical load changes with arm elevation, the assistive torque should vary accordingly rather than remain constant. Second, assistance should be applied selectively. Support is beneficial in overhead postures[35], whereas excessive torque at low arm elevations may hinder natural movement and reduce usability. Assistance should therefore be reduced outside the principal working posture. Third, practical use requires an adjustment method that can accommodate different tasks and users.

Based on these considerations, this study focuses on three design objectives: (i) shaping the assistive torque profile as a function of arm elevation, (ii) reducing interference during non-overhead movements, and (iii) enabling convenient adjustment of the assistance level.

2.2 System Architecture

To meet these requirements, we developed a passive upper-limb exoskeleton with a compact, modular architecture. The overall system is shown in Fig. 2.

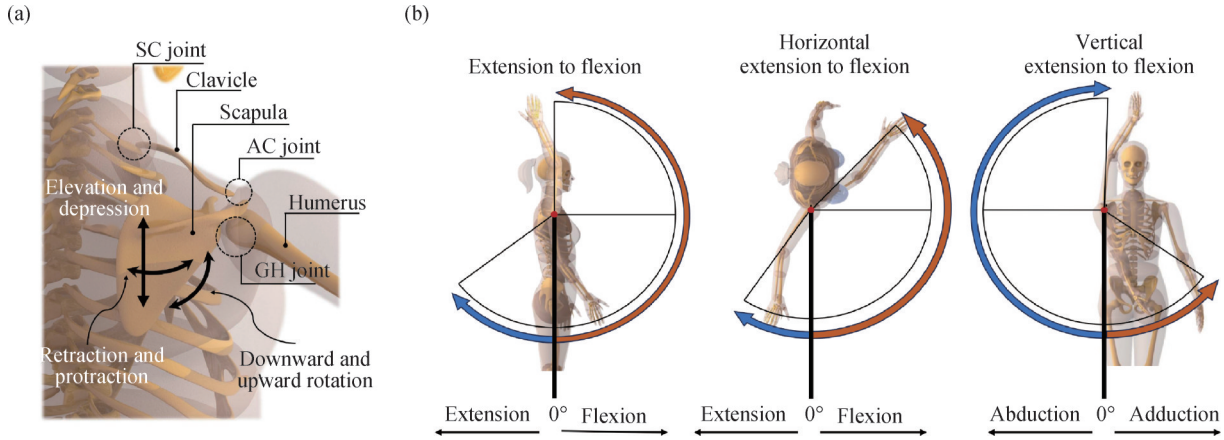


Fig.1 Biomechanical analysis and simplified kinematic representation of the human shoulder complex. (a) Anatomical structure illustrating the coupled motions of the SC, AC, and GH joints along with scapular rotation. (b) Approximation of the high-DOF shoulder system into three primary rotational components—flexion/extension, horizontal flexion/extension, and abduction/adduction—to facilitate assistive device joint design.

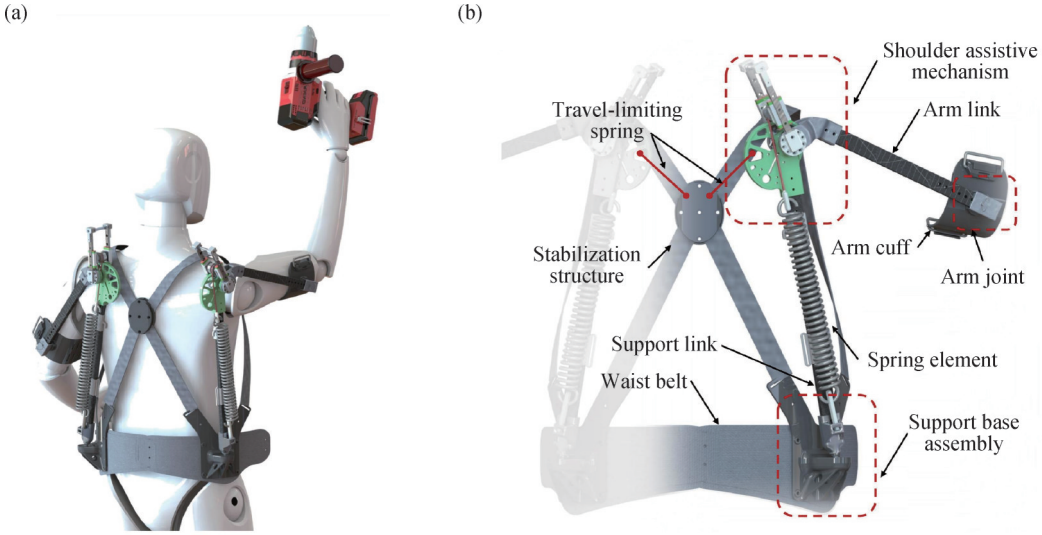


Fig.2 Overview of the shoulder-assistive exoskeleton system. (a) Simulation of the operation scenario illustrating the interaction between the wearer and the device. (b) Detailed system architecture consisting of the load-bearing supporting structure (stabilization structure, arm links, and waist belt) and the shoulder assistive mechanism.

The system is bilaterally symmetric and uses a serial S-R-R configuration to transfer loads from the upper limbs to the torso. It comprises a supporting structure and a shoulder-assistive mechanism. The supporting structure forms the main load-bearing frame and includes a lightweight, high-strength carbon-fiber back frame, two carbon-fiber arm links, adjustable waist straps with biomimetic support pads, and arm cuffs made of breathable, flexible materials. The carbon-fiber components were custom fabricated by Tianhong Carbon Fiber Technology (Shenzhen, China). The assistive mechanism is integrated into the shoulder module and generates a torque that varies with arm elevation. The complete exoskeleton weighs 3.6 kg and provides up to 24 kg of lifting assistance.

The shoulder-assistive mechanism is designed to generate a programmable torque profile, permit unobstructed arm swing, and provide an adjustable assistance level. These functions are implemented by two components: the Cam-based Variable Torque Mechanism (CVTM) and the Ratchet-based Pretension Adjustment Mechanism (RPAM), highlighted by the dashed boxes in Fig. 3.

2.2.1 Cam-based Variable Torque Mechanism (CVTM)

The CVTM generates assistive torque as a function of arm elevation. A 3-mm-diameter Dyneema cable (Shenzhen Yingfu Rope and Webbing Weaving Factory, Shenzhen, China) passes over a moving pulley and connects the spring to a mounting point on the shoulder shaft. The pulley translates along a cam-follower guide fixed to the arm link and frame. Under spring tension, the follower roller remains in contact with the cam profile, so the cam geometry determines the pulley trajectory. This geometry establishes a relationship between spring elongation and arm posture. By designing the cam profile

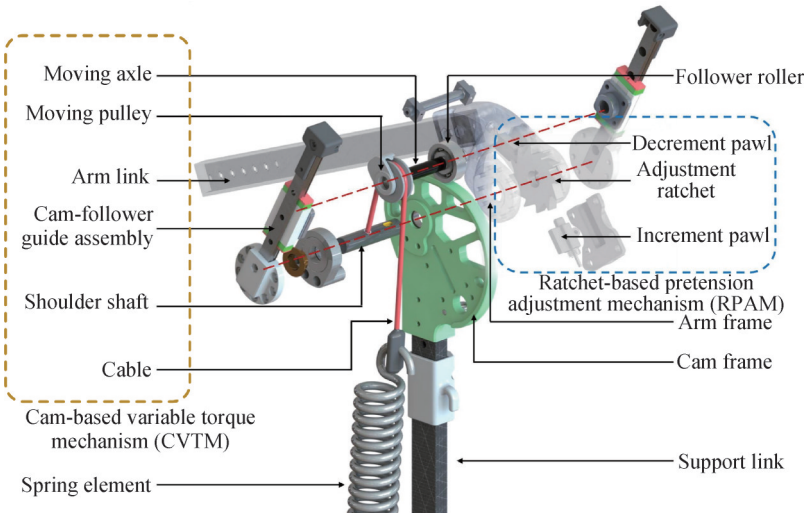


Fig.3 Detailed design of the shoulder assistive mechanism. The assembly integrates the Cam-based Variable Torque Mechanism (CVTM) for generating programmable torque profiles and the Ratchet-based Pretension Adjustment Mechanism (RPAM) for adjustable assistance levels.

appropriately, a prescribed assistive torque curve can be generated.

The CVTM is intended to introduce little resistance during natural arm swing and has a piecewise operating characteristic. As shown in Fig. 4, the transition occurs at $\alpha_E = \theta_r$. When $\alpha_E \leqslant \theta_r$ (the low-assistance phase; Fig. 4a and the blue region in Fig. 4c), the cable partially wraps around the shoulder shaft and effectively acts as a fixed pulley. The arm can therefore swing with low mechanical resistance. When $\alpha_E > \theta_r$ (the overhead-work phase; Fig. 4b and the green and gray regions in Fig. 4c), the mechanism enters the assistive phase and supports arm elevation.

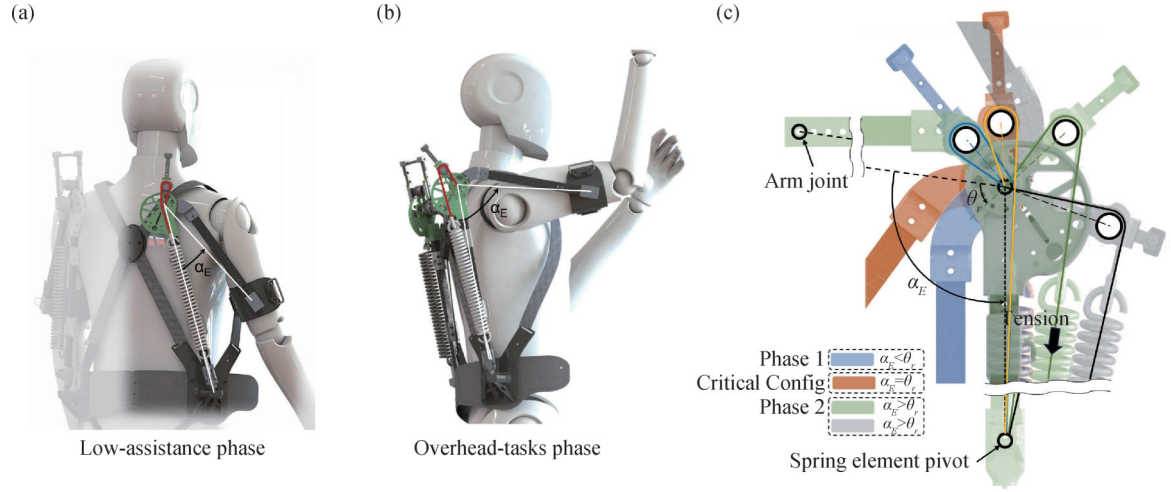


Fig.4 Operation phases and transition logic of the Cam-based Variable Torque Mechanism (CVTM). (a) Low-assistance phase where $\alpha_E < \theta_r$, allowing free arm swing with minimal resistance, highlighting the cable path (red) around the shoulder shaft. (b) Overhead-tasks phase where $\alpha_E > \theta_r$, providing assistive torque for arm elevation. (c) Kinematic transition of the CVTM, showing the critical configuration at $\alpha_E = \theta_r$ (orange) and the progression from Phase 1 (blue, $\alpha_E < \theta_r$) to Phase 2 (green and gray, $\alpha_E > \theta_r$).

2.2.2 Ratchet-based Pretension Adjustment Mechanism (RPAM)

The RPAM adjusts the assistive torque level. As shown in Fig. 5, its main components are an adjustment ratchet and two spring-loaded pawls, referred to as the increment and decrement pawls. Each pawl has two positions: an engaged position, in which it contacts the ratchet, and a standby position, in which it is disengaged.

The RPAM has three operating modes: increment, decrement, and assistive, as shown in Fig. 6. In increment mode (Fig. 6a), both pawls are engaged. The wearer increases the assistance level, and thus the spring pretension, by repeatedly lifting and lowering the arm. During arm elevation, the increment pawl locks the ratchet. During arm lowering, the decrement pawl drives the ratchet, winding the cable around the shoulder shaft and increasing the spring pretension.

In decrement mode (Fig. 6b), both pawls are disengaged, allowing the ratchet to rotate freely. The assistance level can consequently return to its minimum

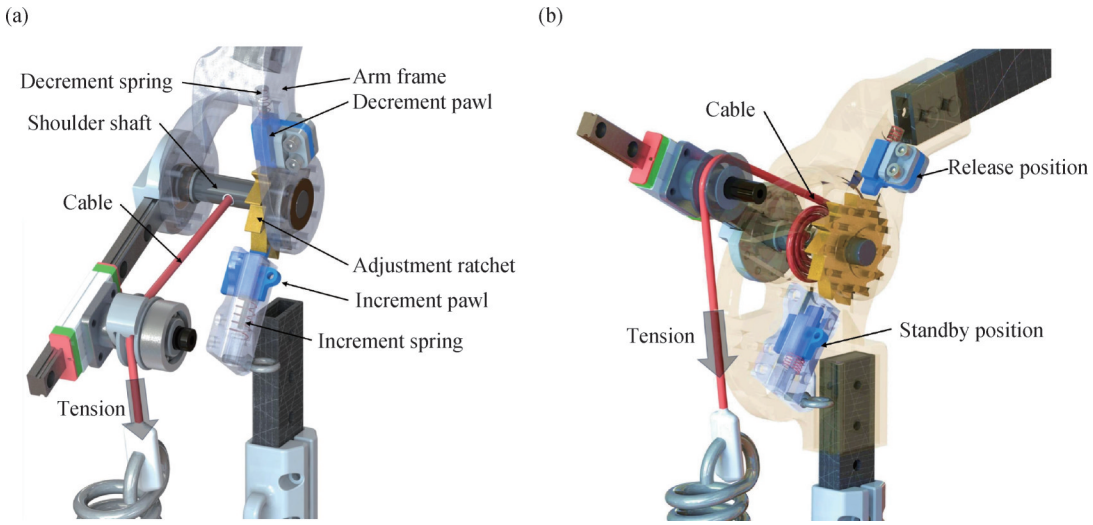


Fig.5 Working states of the Ratchet-based Pretension Adjustment Mechanism (RPAM). (a) Initial state with no pretension, where the cable is not wrapped around the shoulder shaft. (b) Adjusted state with increased pretension, showing the cable wound multiple times around the shaft.

as the cable is pulled in the direction of the spring force, which reduces the pretension.

In assistive mode (Fig. 6c), the decrement pawl is engaged and the increment pawl is disengaged, thereby locking the selected assistance level. In this configuration, the ratchet follows arm motion without relative cable movement, so normal arm swing does not change the spring pretension.

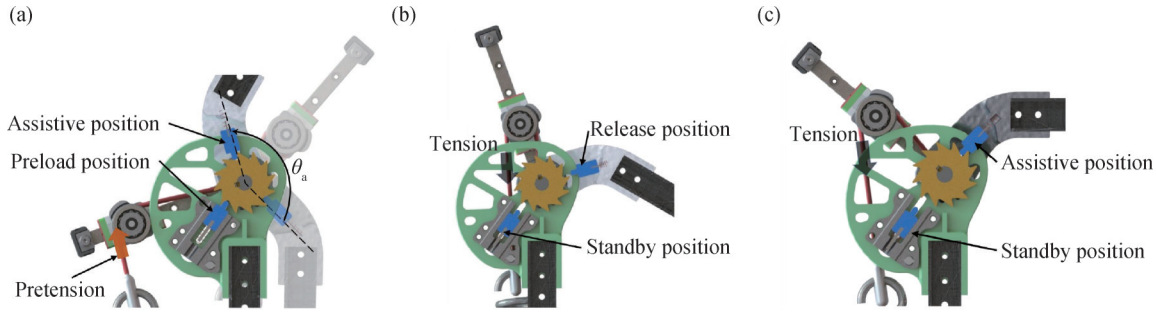


Fig.6 The three operational modes of the Ratchet-based Pretension Adjustment Mechanism (RPAM). (a) Increment mode: Both pawls are engaged (assistive position), allowing spring pretension to increase through cyclic arm motion. (b) Decrement mode: Both pawls are in the standby position (disengaged), enabling the ratchet to reset and the assistive level to return to minimum. (c) Assistive mode: The decrement pawl is engaged while the increment pawl is in the standby position, locking the assistance at a preset level for stable operation.

3 Experimental Methods

3.1 Participants

Five healthy adult male participants were recruited. Their mean age was 30 ± 5 years and their mean body mass was 82 ± 5 kg. None reported a history of shoulder pain, upper-limb musculoskeletal disorders, or neurological impairment that could affect task performance. The experimental protocol was approved by the Medical Ethics Committee of the Shenzhen Institutes of Advanced Technology (SIAT) under Application No. SIAT-IRB-240415-H0741.

3.2 Experimental Tasks

A static arm-holding task was performed. The exoskeleton worn by one participant is shown in Fig. 7. During the task, participants held the right upper arm parallel to the horizontal plane and the forearm perpendicular to it. The plane formed by the upper arm and forearm was aligned with the body sagittal plane, following the protocol of Van Engelhoven et al. [36]. Each trial lasted 2 min. Four conditions were tested: with or without an external load (3 kg) and with or without exoskeleton assistance. Because the assistance level was adjustable, it was standardized across participants to the pretension achieved after 12 lifting cycles.

Surface electromyography (sEMG), upper-arm elevation angle, and metabolic data were recorded. sEMG and inertial measurements were acquired using three integrated ELONXI sensor modules (Jiaopu Technology Co., Ltd., Shenzhen, China), positioned over the teres major, deltoid, and trapezius muscles. Each module used two bipolar input electrodes and one separate reference

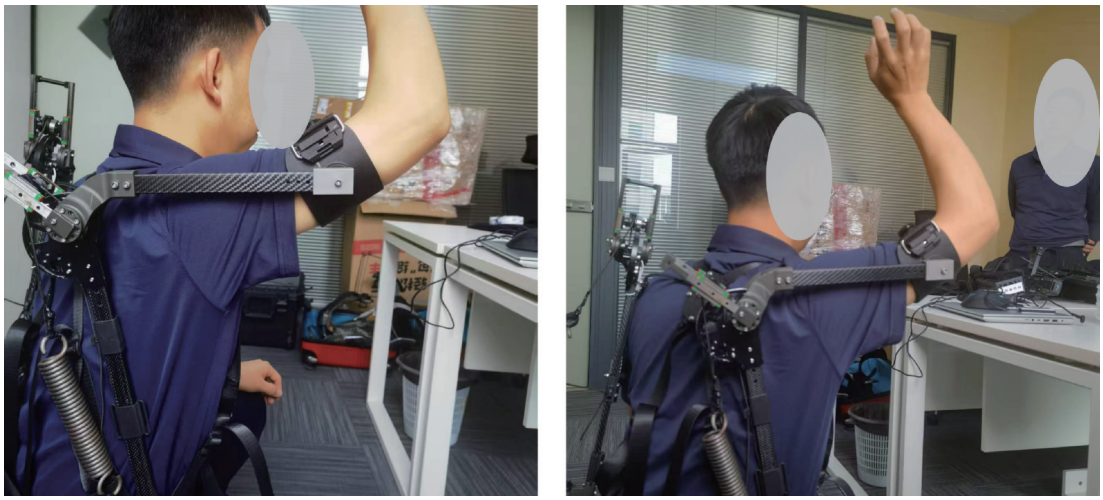


Fig.7 Wearing condition of the exoskeleton.

electrode. The sEMG signals were sampled at 1000 Hz, and the integrated IMUs were sampled at 100 Hz. Metabolic data were collected using a K5 Wearable Metabolic System (COSMED S. r. l., Rome, Italy). The anterior deltoid contributes primarily to shoulder flexion, whereas the latissimus dorsi and teres major contribute to shoulder movement and stabilization. Muscle activation was quantified using the root-mean-square (RMS) amplitude of the EMG signals, and the percentage reduction with assistance was calculated. Postural stability was assessed from the standard deviation of the upper-arm elevation angle during the task. All data were processed using MATLAB R2022b (The MathWorks, Inc., Natick, MA, USA).

4 Results

For the static arm-holding task, Figs. 8-10 show the EMG, IMU, and metabolic results, respectively.

As illustrated in Fig. 8a, assistance reduced activation of all three muscles for most participants under both load and no-load conditions. Under the no-load condition, the mean RMS values of the teres major, deltoid, and trapezius were reduced by 32 ± 26%, 75 ± 17%, and 60 ± 21%, respectively, when assistance was provided. Under the load condition, the corresponding reductions were 18 ± 25%, 55 ± 17%, and 47 ± 28%. The magnitude of the reduction varied between participants, possibly because of differences in movement habits and compensatory strategies. Subject 3 showed increased teres-major activation under the load condition with assistance, which may reflect co-contraction used to stabilize the posture.

Figure 8b presents representative trapezius EMG signals from Subject 3 under the load condition. The signal amplitude was lower when assistance was provided.

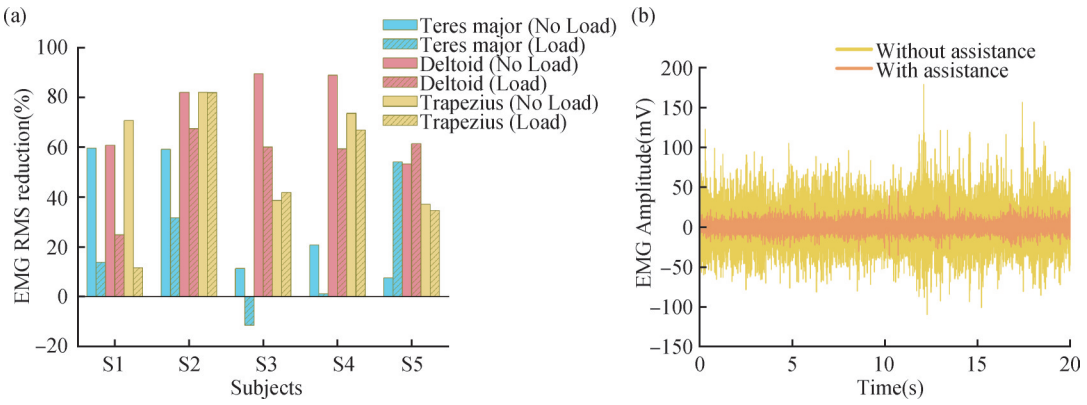


Fig.8 Effect of assistance on muscle EMG activity under load and no-load conditions. (a) Percentage reduction in EMG RMS of the teres major, deltoid, and trapezius muscles with assistance compared to without assistance across subjects (S1-S5) under load and no-load conditions. (b) Representative EMG signals of the trapezius muscle for S3 under the load condition with and without assistance.

The IMU results (Fig. 9a) show that assistance reduced the standard deviation of the upper-arm elevation angle, indicating less variation in arm posture. Data from Subject 5 were excluded because of IMU packet loss. The difference for Subject 4 under the load condition was small, possibly because the subject already maintained a stable posture without assistance. Fig. 9b shows a representative elevation-angle time series for S2. The first

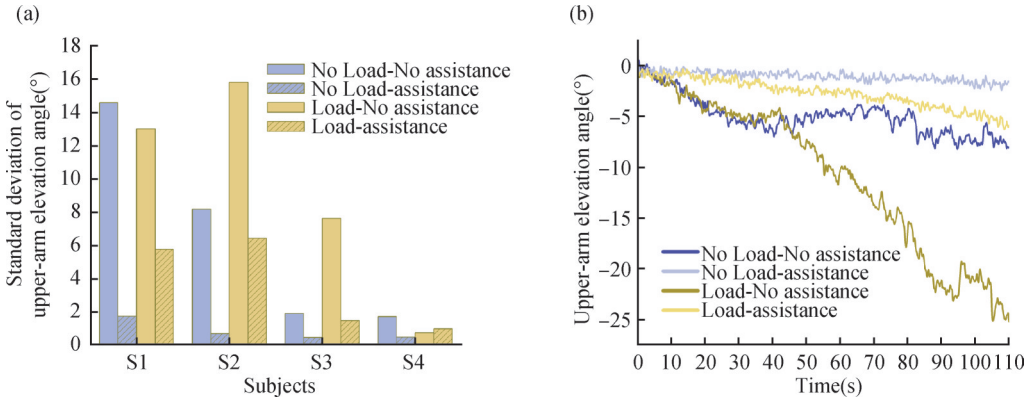


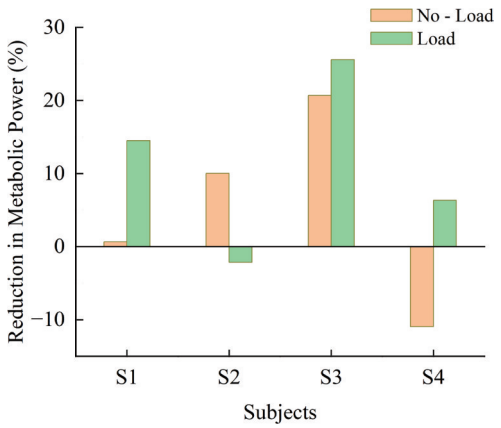
Fig.9 Upper-arm elevation angle measured by IMU under different load and assistance conditions. (a) Standard deviation of the upper-arm elevation angle over a 2-min recording period for each subject, reflecting the variability of arm posture. Four experimental conditions are compared: no load-no assistance, no load-assistance, load-no assistance, and load-assistance. (b) Representative time-series of the upper-arm elevation angle for S2 under the four conditions. The first 10 s of the recording were excluded because the subject was raising the arm.

10 s were excluded to remove the initial posture-adjustment period. Without assistance, the angle gradually decreased and the signal exhibited greater tremor.

Metabolic results are shown in Fig. 10. Baseline metabolic power was recorded during 2 min of quiet standing. Data from Subject 5 were excluded because speaking during the trial invalidated the measurement. Under the load condition (green), assistance reduced metabolic power for S1, S3, and S4 by 15%, 26%, and 6%, respectively, whereas S2 showed a 2% increase. Under the no-load condition (orange), metabolic power decreased by 1%, 10%, and 21% for S1, S2, and S3, respectively, while S4 showed an 11% increase. The metabolic measurements obtained with the K5 system should be interpreted cautiously. The 2-min recording period for each task may have been too short for participants to reach a physiological steady state. Moreover, because the task was relatively low in intensity, normal fluctuations in metabolic power may have influenced the measured differences between conditions. These factors limit the strength of conclusions that can be drawn from the metabolic data.

Subjects	S1	S2	S3	S4
Resting	169.8	197.9	161.7	129.5
No Load, No Assistance	168.4	176.7	187.0	144.4
No Load, Assistance	167.3	159.0	148.3	160.2
Load, No Assistance	180.0	246.4	202.8	178.5
Load, Assistance	153.9	251.7	150.9	167.2
Reduction (%) (No Load)	0.7	10.0	20.7	-10.9
Reduction (%) (Load)	14.5	-2.2	25.6	6.3

(a) Metabolic power under different load and assistance conditions



(b) Reduction in metabolic power with assistance

Fig.10 Metabolic power under different load and assistance conditions. (a) Metabolic power (W) recorded using the K5 system during quiet standing and the four experimental conditions: no load-no assistance, no load-assistance, load-no assistance, and load-assistance. The percentage reduction with assistance relative to the corresponding no-assistance condition is also reported. (b) Reduction in metabolic power across subjects under load and no-load conditions.

5 Discussion

This study presents a passive upper-limb exoskeleton for overhead work. Its main contributions are (1) a cam-based mechanism for designing task-specific torque profiles, (2) a mechanism that limits interference with natural arm motion, and (3) a pretension-adjustment mechanism that allows rapid tuning on the body. The system combines a compact serial structure with contour-driven torque generation and an adjustable spring module.

The main distinction of this work is the treatment of the assistive torque profile as a design variable. In many passive exoskeletons, the torque profile arises implicitly from the geometry of springs, linkages, or cable routings and is therefore difficult to control beyond broad trends. Such systems generally provide assistance that follows

gravitational loading but offer limited freedom to shape the torque distribution for a particular task.

In the present design, the desired assistive torque is specified first, and the mechanism geometry is then selected through the cam contour to approximate that profile. A systematic mapping from a target torque to a cam contour is beyond the scope of this study and will be addressed in future work. This design approach can support nonlinear, piecewise, or deliberately constrained assistance patterns that are difficult to obtain with conventional passive layouts.

This capability is relevant because overhead work is not determined solely by the required peak torque. The effectiveness of assistance also depends on how support is distributed over the arm-elevation range. Excessive torque at low arm angles can hinder natural movement, whereas insufficient torque in the overhead region limits unloading. The assistance profile must therefore be balanced across the working range.

Based on this requirement, the mechanism was designed with a piecewise torque characteristic: low assistance at small arm elevations and increasing assistance as the arm approaches the overhead posture. In practical use, workers frequently transition between working and non-working states, including walking, reaching, and repositioning. Reducing assistance during these phases is expected to limit motion resistance while retaining support during sustained overhead tasks.

The exoskeleton also incorporates a pretension-adjustment mechanism that allows the assistance level to be changed while the device is worn. Assistance requirements vary with task conditions, tool weight, and user preference, whereas many passive systems provide only one fixed level. The proposed mechanism improves this adaptability without adding actuators or electronic control. It does not provide real-time adaptation like an active or semi-active device, but it offers a simple and potentially robust adjustment method.

Compared with prior passive shoulder exoskeletons, which have emphasized kinematic compatibility, range of motion, or remote actuation, this work focuses on mechanism synthesis for torque shaping. The design is organized around the desired assistance behavior rather than around a fixed mechanism architecture. This perspective is useful for task-specific applications in which assistance must be applied selectively or limited over particular motion ranges.

Several limitations should be considered. First, the experimental validation was preliminary and involved only five participants. Second, this study did not present a systematic method for deriving a cam contour from a target torque profile; this remains a topic for future work. Third, the output torque profile was not measured directly, so part of the evaluation relies on indirect measures and mechanism-based interpretation.

Despite these limitations, the design addresses practical requirements of overhead work in aircraft maintenance, manufacturing, and assembly, where sustained arm elevation can cause fatigue and increase injury risk. A compact passive exoskeleton with an adjustable, task-oriented torque profile may provide assistance with low system complexity and maintenance requirements. Future work will include larger user studies, longer task evaluations, quantitative assessment of user acceptance, and systematic cam-design methods for a broader range of task-specific torque profiles.

6 Conclusions

This study presented a passive upper-limb exoskeleton for overhead work that integrates a compact S-R-R structure, a cam-based torque-generation mechanism, and an adjustable pretension module.

The design strategy treats the assistive torque profile as an explicit objective, allowing task-specific and nonlinear assistance to be generated while limiting interference during non-overhead movements.

In the tested static arm-holding task, the system reduced muscle activation and arm-posture variability. The metabolic results varied across participants and provide only preliminary evidence of a reduction in metabolic power. The mechanism was also designed to limit resistance during non-assistive arm motion, although this effect was not measured directly.

Overall, the proposed design provides a passive solution for overhead work with adjustable assistance. Future work will focus on larger-scale validation, extended task evaluations, and systematic methods for cam-contour-based torque-profile design.

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Author Contributions:

Xufei Wang processed the data and wrote the manuscript. Jiying Du conducted the requirements analysis and prepared the experimental conditions. Sida Du designed and manufactured the exoskeleton. All authors contributed to the interpretation of the results and approved the final manuscript.

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Data Availability:

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest:

The authors declare no conflicts of interest related to this work.

References

[1] Shuo Ding, Anaya Reyes Francisco, Tong Li, and Haoyong Yu. A novel passive shoulder exoskeleton for assisting overhead work. *Wearable Technologies* , 4:e7, **2023**.

[2] Junsoo Kim, Juri Kim, Yeongtae Jung, Dongjin Lee, and Joonbum Bae. A passive upper limb exoskeleton with tilted and offset shoulder joints for assisting overhead tasks. *IEEE/ ASME Transactions on Mechatronics* , 27(6): 4963-4973, **2022**.

[3] Thomas Schmalz, Jasmin Schändlinger, Marvin Schuler, Jonas Bornmann, Benjamin Schirrmeister, Andreas Kannenberg, and Michael Ernst. Biomechanical and metabolic effectiveness of an industrial exoskeleton for overhead work. *International journal of environmental research and public health* , 16(23):4792, **2019**.

[4] Morten Wærsted, Markus Koch, and Kaj Bo Veiersted. Work above shoulder level and shoulder complaints: a systematic review. *International Archives of Occupational and Environmental Health* , 93(8):925-954, **2020**.

[5] Julia Mayer, Thomas Kraus, and Elke Ochsmann. Longitudinal evidence for the association between work-related physical exposures and neck and/or shoulder complaints: a systematic review. *International archives of occupational and environmental health* , 85(6):587-603, **2012**.

[6] Kirsten Huysamen, Tim Bosch, Michiel de Looze, Konrad S Stadler, Eveline Graf, and Leonard W O'Sullivan. Evaluation of a passive exoskeleton for static upper limb activities. *Applied ergonomics* , **70**:148-155, **2018**.

[7] Pauline Maurice, Jernej Čamernik, Daša Gorjan, Benjamin Schirrmeister, Jonas Bornmann, Luca Tagliapietra, Claudia Latella, Daniele Pucci, Lars Fritzsche, Serena Ivaldi, et al. Objective and subjective effects of a passive exoskeleton on overhead work. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* , 28(1):152-164, **2020**.

[8] Peng Yin, Liang Yang, Shengguan Qu, and Chao Wang. Effects of a passive upper extremity exoskeleton for overhead tasks. *Journal of Electromyography and Kinesiology* , 55: 102478, **2020**.

[9] Sander De Bock, Marco Rossini, Dirk Lefeber, Carlos Rodriguez-Guerrero, Joost Geeroms, Romain Meeusen, and Kevin De Pauw. An occupational shoulder exoskeleton reduces muscle activity and fatigue during overhead work. *IEEE Transactions on Biomedical Engineering* , 69(10):3008-3020, **2022**.

[10] Lorenzo Grazi, Emilio Trigili, Noemi Caloi, Giulia Ramella, Francesco Giovacchini, Nicola Vitiello, and Simona Crea. Kinematics-based adaptive assistance of a semi-passive upper-limb exoskeleton for workers in static and dynamic tasks. *IEEE Robotics and Automation Letters* , 7(4): 8675-8682, **2022**.

[11] Bernward M Otten, Robert Weidner, and Andreas Argubi-Wollesen. Evaluation of a novel active exoskeleton for tasks at or above head level. *IEEE Robotics and Automation Letters* , 3(3):2408-2415, **2018**.

[12] Yu Meng Zhou, Cameron Hohimer, Tommaso Proietti, Ciarán Tomás O'Neill, and Conor J Walsh. Kinematics-based control of an inflatable soft wearable robot for assisting the shoulder of industrial workers. *IEEE Robotics and Automation Letters* , 6(2):2155-2162, **2021**.

[13] Soumya K Manna and Venketesh N Dubey. Comparative study of actuation systems for portable upper limb exoskeletons. *Medical engineering & physics* , 60(1): 1-13, **2018**.

[14] Lorenzo Grazi, Emilio Trigili, Giulio Proface, Francesco Giovacchini, Simona Crea, and Nicola Vitiello. Design and experimental evaluation of a semi-passive upper-limb exoskeleton for workers with motorized tuning of assistance. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* , 28(10):2276-2285, **2020**.

[15] Jin Tian, Haiqi Zhu, Changjia Lu, Chifu Yang, Yingjie Liu, Baichun Wei, and Chunzhi Yi. A novel passive occupational shoulder exoskeleton with adjustable peak assistive torque angle for overhead tasks. *IEEE Transactions on Biomedical Engineering* , 72(2):734-746, **2025**.

[16] Marco Rossini, Sander De Bock, Arthur van der Have, Louis Flynn, David Rodriguez-Cianca, Kevin De Pauw, Dirk Lefeber, Joost Geeroms, and Carlos Rodriguez-Guerrero. Design and evaluation of a passive cable-driven occupational shoulder exoskeleton. *IEEE Transactions on Medical Robotics and Bionics* , 3(4):1020-1031, **2021**.

[17] Stefania Spada, Lidia Ghibaudo, Silvia Gilotta, Laura Gastaldi, and Maria Pia Cavatorta. Investigation into the applicability of a passive upper-limb exoskeleton in automotive industry. *Procedia Manufacturing* , 11:1255-1262, **2017**.

[18] Dong Jin Hyun, KiHyeon Bae, KyuJung Kim, Seungkyu Nam, and Dong-hyun Lee. A light-weight passive upper arm assistive exoskeleton based on multi-linkage spring-energy dissipation mechanism for overhead tasks. *Robotics and Autonomous Systems* , 122:103309, **2019**.

[19] Ilaria Pacifico, Alessandro Scano, Eleonora Guanziroli, Matteo Moise, Luca Morelli, Andrea Chiavenna, Duane Romo, Stefania Spada, Giuseppe Colombina, Franco Molteni, et al. An experimental evaluation of the proto-mate: a novel ergonomic upper-limb exoskeleton to reduce workers' physical strain. *IEEE robotics & automation magazine* , 27(1): 54-65, **2020**.

[20] Joshua Hull, Ranger Turner, and Alan T Asbeck. Design and

preliminary evaluation of two tool support arm exoskeletons with gravity compensation. *Mechanism and Machine Theory* , 172:104802, **2022**.

[21] Ke Shi, Jun Yang, Zhimin Hou, and Haoyong Yu. Design and evaluation of a four-dof upper limb exoskeleton with gravity compensation. *Mechanism and Machine Theory* , 201: 105746, **2024**.

[22] Jianfeng Li, Qiang Cao, Mingjie Dong, and Chunzhao Zhang. Compatibility evaluation of a 4-dof ergonomic exoskeleton for upper limb rehabilitation. *Mechanism and Machine Theory* , 156:104146, **2021**.

[23] Yijia Peng and Wanghui Bu. Design of gravity-balanced exoskeletons with linkage-belt hybrid transmissions. *Mechanism and Machine Theory* , 170:104660, **2022**.

[24] Skelex. Skelex products. [Online]. *Available online:* https://www.skelex.com/products(accessed on 24 September **2026**).

[25] Ottobock. Ottobock shoulder exoskeleton for overhead work. [Online]. *Available online:* https://www.exoskelette.com/en/exoskeletons/ottobock-shoulder/(accessed on 24 September **2026**).

[26] CRIMSON DYNAMICS. Cdys-s2. [Online]. *Available online:* https://www.c-dyn.com/cn/h-col-133.html(accessed on 24 September **2026**).

[27] Sunwook Kim, Maury A Nussbaum, Mohammad Iman Mokhlespour Esfahani, Mohammad Mehdi Alemi, Saad Alabdulkarim, and Ehsan Rashedi. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part i- "expected" effects on discomfort, shoulder muscle activity, and work task performance. *Applied ergonomics* , 70:315-322, **2018**.

[28] Joao Pedro Pinho and Arturo Forner-Cordero. Shoulder muscle activity and perceived comfort of industry workers using a commercial upper limb exoskeleton for simulated tasks. *Applied Ergonomics* , 101:103718, **2022**.

[29] Michael J Jorgensen, Nils A Hakansson, and Jaydip Desai. The impact of passive shoulder exoskeletons during simulated aircraft manufacturing sealing tasks. *International Journal of Industrial Ergonomics* , 91:103337, **2022**.

[30] Michael J Jorgensen, Nils A Hakansson, and Jaydip Desai. Influence of different passive shoulder exoskeletons on shoulder and torso muscle activation during simulated horizontal and vertical aircraft squeeze riveting tasks. *Applied Ergonomics* , 104:103822, **2022**.

[31] Sander De Bock, Jo Ghillebert, Renée Govaerts, Shirley A Elprama, Uros Marusic, Ben Serrien, An Jacobs, Joost Geeroms, Romain Meeusen, and Kevin De Pauw. Passive shoulder exoskeletons: More effective in the lab than in the field? *IEEE Transactions on Neural Systems and Rehabilitation Engineering* , 29:173-183, **2021**.

[32] Greta Vazzoler, Pietro Bilancia, Giovanni Berselli, Marco Fontana, and Antonio Frisoli. Analysis and preliminary design of a passive upper limb exoskeleton. *IEEE Transactions on Medical Robotics and Bionics* , 4(3):558-569, **2022**.

[33] Ali Nasr, Spencer Ferguson, and John McPhee. Model-based design and optimization of passive shoulder exoskeletons. *Journal of Computational and Nonlinear Dynamics* , 17(5): 051004, **2022**.

[34] Yu Zhu, Felix Balser, Ming Shen, and Shaoping Bai. Design and evaluation of a novel passive shoulder exoskeleton based on a variable stiffness mechanism torque generator for industrial applications. *Robotics* , 13(8):120, **2024**.

[35] Jason R Grieve and Clark R Dickerson. Overhead work: Identification of evidence-based exposure guidelines. *Occupational Ergonomics* , 8(1):53-66, **2008**.

[36] Logan Van Engelhoven and Homayoon Kazerooni. Design and intended use of a passive actuation strategy for a shoulder supporting exoskeleton. *In 2019 Wearable Robotics Association Conference (WearRAcon)* , pp. 7-12, **2019**.