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RESEARCH ARTICLE

Pilot study on Exoskeleton Biomechanics in a Young Population: Variations in Frequency, Speed, Force, and Power during a Physical movement

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ABSTRACT

Musculoskeletal disorders (MSDs) are a leading cause of occupational disability and require effective preventive strategies. Passive exoskeletons are useful devices designed to reduce the biomechanical load while performing physical tasks. This study assessed the biomechanical impact of a passive shoulder exoskeleton on 16 healthy young adults (median age, 26 ± 3 years; 9 males and 7 females), stratified by age and sex. Participants performed repetitive shoulder flexion-extension movements (0°–180°) while lifting a 2 kg load for 20 s, both with and without exoskeleton assistance. Movement frequency, velocity, force, and mechanical power were recorded using the MuscleLab system. The results showed age- and sex-specific responses to the exoskeleton use. Males aged less than 26 years and females generally showed significant improvements in all biomechanical parameters when using the exoskeleton, whereas the other males reported reductions. Statistical analysis revealed significant sex differences in frequency and force ($p < 0.05$). These findings indicate that passive exoskeletons enhance biomechanical performance, particularly in females and males under 26 years of age, whereas the effects observed in other males tend to be negative. This variability highlights the importance of ergonomic customization tailored to user characteristics. Further research with larger cohorts is needed to confirm these findings and optimize the exoskeleton design to improve occupational health outcomes.

Keywords: Biomechanics, exoskeleton, musculoskeletal system, occupational health.

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1. Introduction

Musculoskeletal disorders (MSDs) are among the leading causes of work-related disabilities and significantly affect productivity and occupational health (Hagberg *et al.*, 2012; Crea *et al.*, 2021). Effective prevention strategies require a comprehensive approach that includes classification, risk assessment, and health surveillance (Hagberg *et al.*, 2012). Exoskeletons have emerged as innovative wearable devices that are designed to assist the human body in performing physically demanding tasks. Their application in occupational settings has shown potential not only for primary prevention by reducing biomechanical load but also for secondary and tertiary prevention by alleviating existing musculoskeletal complaints (Steinhilber *et al.*, 2020). These devices can be categorized into passive systems, which redistribute loads mechanically, and active systems, which integrate actuators to augment human motion.

The deployment of exoskeletons is attracting attention across diverse industries, including agriculture, where workers face a high MSD risk due to repetitive motions and awkward postures (Arachchige *et al.*, 2024). Several studies have demonstrated the potential of exoskeletons to reduce muscle fatigue, joint pain, and injury risk, while increasing task endurance (De Bock *et al.*, 2023). More broadly, exoskeletons may also have positive effects on productivity, work quality, and economic outcomes, as shown in recent systematic reviews (Fournier *et al.*, 2023). However, from a biomechanical standpoint, it is essential to quantify these effects using measurable parameters such as force, speed, and muscle power. This study aimed to assess whether the use of a passive shoulder exoskeleton leads to a reduction in musculoskeletal workload, characterized by decreases in muscle-generated power, force, and movement velocity, and to determine whether these effects vary by age group and sex.

2. Materials and Methods

2.1. Subjects

A total of 16 healthy adults with no musculoskeletal disorders based on their medical history were enrolled between January and April 2025 and were assessed by a single physician (R.C.) specialized in Posturology and Occupational Health, in the IRCCS San Gerardo dei Tintori, Monza, Italy. All participants underwent a comprehensive musculoskeletal ultrasound examination of the shoulders to assess the integrity of the rotator cuff tendons (supraspinatus, infraspinatus, teres minor, subscapularis, and long head of the biceps tendon). The examination was performed using a high-frequency linear probe (7.5 MHz–12 MHz) by a physician (J.M.) specifically trained in musculoskeletal ultrasound using an Esaote MyLabTwice ultrasound system (Flexo Medical, Verona, Italy). This evaluation allowed the exclusion of pre-existing soft tissue injuries that might interfere with biomechanical performance.

2.2. The Exoskeleton MATE-XT

MATE-XT (Comau, Torino, Italy) is a passive upper-limb occupational exoskeleton designed to support workers during tasks involving frequent or prolonged arm elevation, particularly in industrial settings. The device was worn as a backpack-like structure with a lightweight rigid frame resting on the user's torso and shoulders. Load transfer occurs through shoulder straps and a waist belt, allowing forces generated by the device to be distributed across the trunk and pelvis rather than across the upper limbs. The exoskeleton had an overall mass of approximately 3 kg, which was intentionally kept low to minimize user fatigue and interference with natural movements. Assistance was provided via a spring-based torque-generator box integrated into the posterior section of the device. This purely mechanical system stores energy when the arms are lowered and releases it during arm elevation, generating a supportive torque at the shoulder joint without the use of motors, electronics, or batteries. Mechanical assistance was transmitted to the arms through articulated linkages connected to the arm cuffs, which were positioned on the upper arms. These linkages are designed to align with the anatomical shoulder joint, enabling support during shoulder flexion and abduction, while preserving a relatively natural range of motion. The level of assistance can be adjusted manually to accommodate different user and task demands. MATE-XT provides its maximum supportive torque at approximately 90° of arm elevation, a posture commonly associated with overhead work, and increased shoulder muscle activation. By reducing the load on the key shoulder muscles, particularly the deltoid and trapezius, the device aims to decrease muscular effort and fatigue during repetitive or sustained overhead activities, as previously described. Importantly, because the system is passive, it does not actively drive movement but rather supports the user's motion, allowing full control to remain with the wearer (Garosi *et al.*, 2024).

2.3. MuscleLab Test

The MuscleLab test was conducted using surface electromyography (sEMG) coupled with a linear encoder, enabling measurement of muscle force and power generation during movement over time. The MuscleLab unit (model 4000e, Ergotest Technology, Norway) supports inputs for EMG sensors and angle sensors and is interfaced with a computer running the MuscleLab software (version 10.251.117.5396). Surface electrodes (model T916, teardrop-shaped, 43 mm × 45 mm, with an inter-electrode distance of approximately 2 cm) produced by Bio Protech Inc. were used, and the hydrogel was applied to ensure adhesion to the skin. Electrodes were positioned on the deltoid, triceps, and multifidus muscles in accordance with the sensor placement guidelines outlined by the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SE-NIAM) project. The assessment protocol consisted of continuous repetitions of shoulder flexion-extension movements through a 0°–180° range of motion over a 20-second period, during which all the participants were instructed to lift and lower a 2 kg load with and without the assistance of the passive exoskeleton MATE-XT. The objective was to determine the maximum number of cycles within the allowed time. This protocol was designed to simulate repetitive overhead work and allow a direct comparison of shoulder kinematics and muscular demands with or without assistance conditions. The choice of a 2 kg load and 20 s movement period is a methodological decision supported by existing experimental practices in biomechanics and ergonomics research, as previously reported (Pascoal *et al.*, 2000; Grazi *et al.*, 2024). During movements, the software recorded the number of repetitions (Frequency, Hz), execution speed (velocity, m/s), force (N), and mechanical power (W). The results obtained from the instrument show the standard deviations of the force and power values of each cycle movement.

2.4. Statistical Analysis

Statistical analyses were performed using MedCalc for Windows, version 19.4 (MedCalc Software, Ostend, Belgium). Comparisons between groups (with and without the assistance of the passive exoskeleton, age, and sex) were performed using the chi-squared (χ^2) test and Fisher's exact test. Statistical significance was set at $P < 0.05$.

3. Results

Sixteen healthy young adults (median age, 26 ± 3 years; 9 males, 7 females) were enrolled in the study. Initial musculoskeletal ultrasound examinations confirmed the absence of soft tissue injuries in all subjects. During the

TABLE I: Analysis of Data in the Group of the Subjects Enrolled in the Study

	Males ($n = 9$)						Females ($n = 7$)					
	Age < 26 years ($n = 4$)			Age > 26 years ($n = 5$)			Age < 26 years ($n = 4$)			Age > 26 years ($n = 3$)		
	Decreased	Unchanged	Increased	Decreased	Unchanged	Increased	Decreased	Unchanged	Increased	Decreased	Unchanged	Increased
Frequency (n)	1	2	1	1	0	4	3	0	1	3	0	0
Velocity (n)	4	0	0	1	1	3	4	0	0	3	0	0
Force (n)	4	0	0	1	0	4	3	0	1	3	0	0
Power (n)	4	0	0	1	0	4	4	0	0	3	0	0
Total (n)	13	2	1	4	1	15	14	0	2	12	0	0

shoulder flexion-extension task, which was performed both with and without passive exoskeleton assistance, four biomechanical parameters, movement frequency, execution velocity, force, and mechanical power, were recorded using the MuscleLab system.

Participants were stratified by age and sex, with eight subjects younger than 26 years (median age 24 ± 1 years; 3 males, 5 females) (Group 1) and eight subjects aged ≥ 26 years (median age 28 ± 2 years; 6 males, 2 females) (Group 2), representing pre-university graduation and post-university graduation with an initial job in the hospital, respectively. Table I describes the number of subjects with decreased, unchanged, or increased biomechanical parameter values in the different sex and age subgroups before and after using the exoskeleton. Among the males in Group 1, the majority exhibited decreases in velocity, force, and power when using the exoskeleton. Conversely, males in Group 2 demonstrated predominantly increased frequency, velocity, force, and power. In all females, we observed decreased values across all parameters.

Comparative analysis between the sexes revealed that males generally exhibited more variability in response to exoskeleton assistance, with a significant proportion showing increased performance, particularly in the younger age group. On the other hand, all females showed predominantly decreased values both in Group1 and Group 2.

Table II lists the average changes in each parameter: frequency, velocity, force, and power. Negative changes were interpreted as beneficial, reflecting a reduction in muscular workload, whereas positive changes indicated an increase in biomechanical demand, suggesting a lack of benefit, or even a potentially adverse effect. Participants in the group that reported decreased values experienced consistent reductions in all parameters. These data suggest that the device effectively supported shoulder movements in these individuals by lowering the muscular effort. In contrast, those in the unchanged group showed minor differences in performance metrics before and after exoskeleton use, indicating a neutral effect of the device on biomechanical load. Subjects in the increased group demonstrated a worsening of biomechanical parameters, suggesting that rather than assisting movement, the exoskeleton increased the mechanical demand in these individuals. Statistical comparisons among the three groups confirmed that these differences were significant for all measured variables ($p < 0.05$).

4. Discussion

The present pilot study investigated the effects of a passive exoskeleton on shoulder flexion-extension performance in 16 young healthy adults stratified by age and sex. Our findings revealed age- and sex-specific biomechanical responses to passive exoskeleton use. Among adults aged < 26 years, both males and females showed decreased power, force, and velocity. This pattern may reflect neuromuscular adaptation to the mechanical load path induced by the exoskeleton. Conversely, males aged greater than 26 years exhibited significantly increased values across all measured parameters, including frequency, velocity, force, and power, suggesting that the exoskeleton provided decreased performance support in this subgroup. In contrast, females aged greater than 26 years experienced reductions in force, speed, and power, highlighting enhanced performance. These trends were further clarified by analyzing the mean changes in biomechanical parameters. Participants who showed decreased values after exoskeleton use ($n = 8$) demonstrated clear biomechanical improvements, reflected in lower muscle effort across all metrics: frequency (−0.03 Hz ± 0.02 Hz), velocity (−0.13 m/s ± 0.10 m/s), force (−2.23 N ± 2.06 N), and power (−6.84 W ± 5.24 W). These reductions are indicative of a reduced musculoskeletal workload, which is consistent with the intended supportive function of the passive exoskeleton.

On the other hand, subjects with increased values ($n = 6$) experienced worsening of bio-mechanical parameters, with higher muscle output requirements: frequency rose by 0.03 Hz ± 0.01 Hz, velocity by 0.02 m/s ± 0.05 m/s, force by 0.42 N ± 1.13 N, and power by 0.94 W ± 3.07 W. These data suggest that for a subset of participants, the exoskeleton may have been ergonomically ineffective, potentially increasing the mechanical effort.

These discrepancies align with broader discussions in the literature regarding the interaction between user characteristics and device effectiveness, particularly in relation to productivity and long-term usability (Fournier *et al.*, 2023). Consistent with these findings, Garosi *et al.* (2024) demonstrated that passive head/neck supporting exoskeletons can significantly modify muscle fatigue thresholds during repetitive overhead tasks, highlighting the variability of biomechanical assistance effects depending on the task and user characteristics (Moeller *et al.*, 2022). Furthermore, Moeller and coauthors in their literature review on upper-limb exoskeletons designed for occupational use, observed the necessity of tailoring exoskeleton designs to specific working environments and user populations to maximize effectiveness and adoption (Moeller *et al.*, 2022).

TABLE II: Mean of the Differences of the Variables in the Different Group of Subjects after Using the Exoskeleton

Variable	Decreased ($n = 8$) (Mean ± SD)	Unchanged ($n = 2$) (Mean ± SD)	Increased ($n = 6$) (Mean ± SD)	p-value
Frequency (Hz)	−0.03 ± 0.02	0.00 ± 0.00	0.03 ± 0.01	0.007
Velocity (m/s)	−0.13 ± 0.10	−0.04 ± 0.01	0.02 ± 0.05	0.027
Force (N)	−2.23 ± 2.06	−0.60 ± 0.30	0.42 ± 1.13	0.029
Power(W)	−6.84 ± 5.24	−1.81 ± 0.57	0.94 ± 3.07	0.029

Note: SD, Standard Deviation. See *Materials and Methods* for details.

The expanding applications of exoskeletons in sectors such as agriculture further underscores this need (Arachchige *et al.*, 2024). Preventive strategies and health surveillance remain vital for reducing musculoskeletal disorders in the workplace (Hagberg *et al.*, 2012).

Our findings agree with the recent advances in passive exoskeleton design aimed at optimizing biomechanical support in occupational settings. Notably, van Sluijs *et al.* (2024) developed and evaluated OmniSuit, a passive occupational exoskeleton that provides combined back and shoulder support. Their study demonstrated improved ergonomic outcomes and reduced muscular strain during physically demanding tasks, highlighting the importance of a device design that accommodates multiple body regions to enhance user comfort and performance (van Sluijs *et al.*, 2024). This supports our observation that exoskeleton effectiveness is highly dependent on ergonomic compatibility and user-specific biomechanics, particularly regarding sex and age differences. Integrating multi-joint support and customizable features, as suggested by van Sluijs *et al.*, could address the performance discrepancies observed in older males in our cohort, potentially improving acceptance and effectiveness across diverse worker populations (van Sluijs *et al.*, 2024).

Because the study was conducted at a single center with a limited sample size, the applicability of our findings to broader populations is limited. Larger multicenter clinical studies are required to validate and refine these observations. Nonetheless, our results suggest that passive exoskeleton assistance may effectively reduce the musculoskeletal workload in a portion of our enrolled population, particularly in younger males and females.

5. Conclusions

The effects of passive shoulder exoskeletons on biomechanical performance are significantly influenced by user-specific factors, such as age and gender. While males under 26 years of age and all female subjects generally exhibited reductions in power and velocity, suggesting decreased muscular workload, the others tended to show increased values, indicating less benefit or potentially negative effects from exoskeleton use. This heterogeneity in response highlights that passive exoskeletons may not provide uniform benefits to all users and underlines the importance of customized device designs. Future research should focus on understanding the neuromechanical mechanisms underlying these differences and developing ergonomic, adaptable exoskeletons tailored to diverse worker populations and specific occupational needs, ensuring both safety and effectiveness in the workplace.

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Declaration of AI Usage

The authors declare that AI tools have been used for grammar correction and language editing. The intellectual content, analyses, and conclusions are the authors' own.

Author Contributions

Conceptualization, R.C. and J.I.; methodology, R.C., J.M., and S.P.; data curation, R.C., J.M., S.P., and J.I.; writing—original draft preparation, R.C. and J.I.; writing—review and editing, R.C. and J.I.; supervision, M.A.R., M.B., and M.E.P.., J.M., S.P., and M.I.D. All authors have read and agreed to the published version of the manuscript.

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Informed Consent

The local ethics committee did not require informed consent due to the nature of paper where retrospective de-identified data were used.

Data Availability

Dataset available on request from the authors.

Conflict of Interest

The authors declare no conflict of interest.

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