

Active, Quasi-Passive, Pneumatic, and Portable Knee Exoskeleton with Bidirectional Energy Flow for Efficient Air Recovery in Sit-Stand Tasks

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Abstract—While existing literature encompasses exoskeleton-assisted sit-stand tasks, the integration of energy recovery mechanisms remains unexplored. To push the boundaries further, this study introduces a portable pneumatic knee exoskeleton that operates in both quasi-passive and active modes, where active mode is utilized for aiding in standing up (power generation), thus the energy flows from the exoskeleton to the user, and quasi-passive mode for aiding in sitting down (power absorption), where the device absorbs and can store energy in the form of compressed air, leading to energy savings in active mode. The absorbed energy can be stored and later reused without compromising exoskeleton transparency in the meantime. In active mode, an air pump inflates the pneumatic artificial muscle (PAM), which stores the compressed air, that can then be released into a pneumatic cylinder to generate torque. All electronic and pneumatic components are integrated into the system, and the exoskeleton weighs 3.9 kg with a maximum torque of 20 Nm at the knee joint. The paper describes the mechatronic design, mathematical model and includes a pilot study with an able-bodied subject performing sit-to-stand tasks. The results show that the exoskeleton can recover energy while assisting the subject and reducing mean muscle activity by $\sim 31\%$. Further results highlight air regeneration's potential for energy saving in portable pneumatic exoskeletons, showing that the proposed device extends exoskeleton operation by $\sim 27\%$.

I. INTRODUCTION

Efficient energy utilization is a crucial consideration in every technical system. Human joints can both generate and absorb power, which opens up the space for energy recovery. For example, regenerative exoskeletons can capture otherwise wasted human energy and produce electricity when backdriven by joint movements during negative power intervals [1]–[5]. While most of these devices primarily target energy recovery during walking, Laschowski et al. [6] highlighted the potential of energy recovery during sitting transfers where the hip, knee, and ankle power is almost entirely negative, while standing up requires positive joint power [7]. Existing literature covers exoskeletons-assisted stand-to-sit tasks, yet without any energy recovery [8]–[12]. This absence in the literature may be attributed to the large number of required sitting repetitions in order to notice the effect, mainly because of the limited efficiency in converting

mechanical to electrical power. Namely, robotic exoskeletons could theoretically regenerate ~ 26 joules per single sitting task, meaning that with 60 repetitions, this merely extends the exoskeleton operation by around $\sim 0.7\%$ [6]. Another, more efficient, type of energy storing and reusing is found in quasi-passive exoskeletons which absorb kinetic energy within elastic components during negative power intervals and subsequently return it to the joints in positive power intervals with the help of clutches [5], [13]–[18]. This process minimizes losses as kinetic energy is directly converted into elastic energy and vice versa. Yet, even though highly efficient in energy recovery, they cannot produce net positive work like robotic actuators, and relying solely on recovered energy may sometimes be insufficient.

However, pneumatic actuators, like cylinders, exhibit the versatility to function as both elastic components (air springs) and force-generating actuators. This implies they could provide a good pathway for combining efficient energy recovery with the ability to produce positive net mechanical work. Moreover, the air is a lightweight elastic medium that can be easily passed to another energy reservoir and stored. Therefore, when positive power generation is required, a portion of the stored air can be retrieved from a storage tank, minimizing the need for additional compressed air generation by the pump, thus reducing energy consumption.

In an optimal scenario, exoskeleton-assisted sit-stand task include: assistance with energy absorption (in the Exo) when sitting down, efficient energy storing for future use, enabling transparency without energy loss, and actively assisting in standing up partially reusing stored energy, which would reduce overall consumption. To achieve this, we design a portable pneumatic exoskeleton that operates as active, quasi-passive, and transparent while keeping energy. In the literature, pneumatic actuators have been utilized in the active [19], [20] and quasi-passive exoskeletons [14], [15], [21]. They are appealing due to their high weight-to-power ratio, inherent compliance, and high backdrivability. Still, when used as active the necessity for an air tank poses portability challenges for pneumatic exoskeletons. Notably, a few prior studies have successfully devised active portable pneumatic exoskeletons integrating onboard air compressors and metal air tanks; [22] weighing 9.12 kg, [23] weighing 9.95 kg. Our previous work developed a method for modulating air spring stiffness by drawing air from the atmosphere without an air pump or supply. The method was applied in the variable stiffness joint mechanism [21]. Here we introduce, the JSI-KneExo with key **contributions** as follows:

- 1) Introducing an Exo that enables bidirectional energy

This work was supported by grants from the Slovenian Research Agency; PR-10489, and N2-0153. Video attachment available along with the paper.

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flow between the user and exoskeleton, allowing highly efficient energy recovery in the form of compressed air while simultaneously assisting the user. Energy recovery ultimately leads to big overall energy savings.

- 2) Design is enabled by a pneumatic air regenerative actuator integrated into a lightweight, slim, and portable knee exoskeleton that can switch between different modes, such as active, quasi-passive, or transparent, which is mathematically described.

II. THEORETICAL ANALYSIS

A. Exoskeleton Design

The JSI-KneExo (Fig. 1a) is a modular system made up of three major components: the left-leg exoskeleton with an actuator, the right-leg exoskeleton with an actuator, and the control unit. Depending on the application, one or both legs of the exoskeleton may be used simultaneously. The whole system weighs 3.9 kg (each leg of the exoskeleton 1.25kg and the control unit 1.4kg). The range of motion is 0 - 135°.

1) *The actuator unit:* The actuator (Fig. 1b) comprises a pneumatic cylinder (DNSU-25-100-PPV-A, FESTO, Germany), which generates force when pressurized air enters its chamber. As the cylinder is attached to the shank and thigh levers, the force in the cylinder causes torque in the joint with a maximum value of 20 Nm at a maximum pressure of 8 bar. The cylinder has a maximum stroke of 100 mm and a bore diameter of 25 mm. The compressed air generated by the air pump is stored in the pneumatic artificial muscle (PAM), DMSP-20-100N-RM-RM (initial diameter 20mm, initial length 100mm), which when inflated shrinks its length and increases its diameter. The PAM's lower end is fixed, upper-end slides on the linear bearing. Each unit contains two

solenoid air valves (MHE2-MS1H-3/2O-QS-4-K, FESTO, Germany) for state change, as detailed further in the paper. The absolute encoder AS5600 (ams-OSRAM AG, Austria) measures the joint angle, while the cylinder force is measured by the force sensor ZMME-S100 (Zhiminsensor, China).

2) *The control unit:* The control unit is shown in (Fig. 1c). The JSI-KneExo is fully portable as the compressed air is supplied by the air pump BD-04A-20L, BodenFlo, China, driven by a 12 V LiPo battery. If running continuously, the pump has an autonomy of ~3.4 h. Six MOSFET switches, arranged in two PCBs control solenoid valve positions. An extra solenoid valve is included in the control unit box, the function of which is explained in the next section. A pressure sensor is integrated to continuously monitor the pressure in both PAMs. The voltage is converted to 24 V for the solenoid valves by the DC-DC converter. The main microcontroller is an Arduino Mega 2560.

B. Portable pneumatic design

The portable pneumatic circuit is shown in Fig. 2. All five solenoid valves are identical and monostable, transitioning smoothly between '1' and '2' positions with a ~2 ms frequency. The air pump generates compressed air, which charges the PAM, and pressure is tracked using a sensor. The valve P depressurizes the tube after air pumping; otherwise, by restarting the pump the reverse pressure holds the pump back when it needs the most power. Symmetrical pneumatic connections exist on both sides (left and right). Different valve combinations achieve various states. For example, in "Release all" both valves 1 and 2 are set to '1', allowing atmospheric pressure to enter the cylinder and PAM, resulting in air release. The second state, "Hold Air,

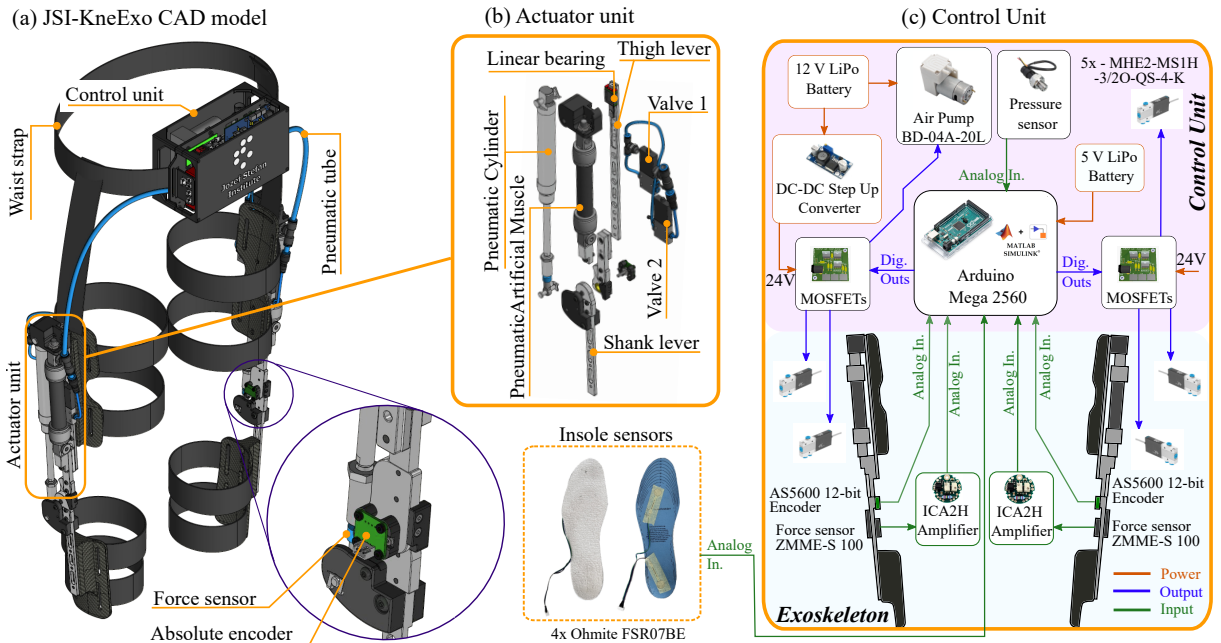


Fig. 1. (a) The JSI-KneExo comprises three modular parts: control unit, left-leg exoskeleton, and right-leg exoskeleton. (b) The actuator unit incorporates air solenoid valves, PAM, pneumatic cylinder, force sensor, absolute encoder, PAM, and a linear bearing facilitating linear PAM deflection. (c) Pink background highlights control unit components, while light blue denotes exoskeleton (leg side) components; optional insole sensors can be added.

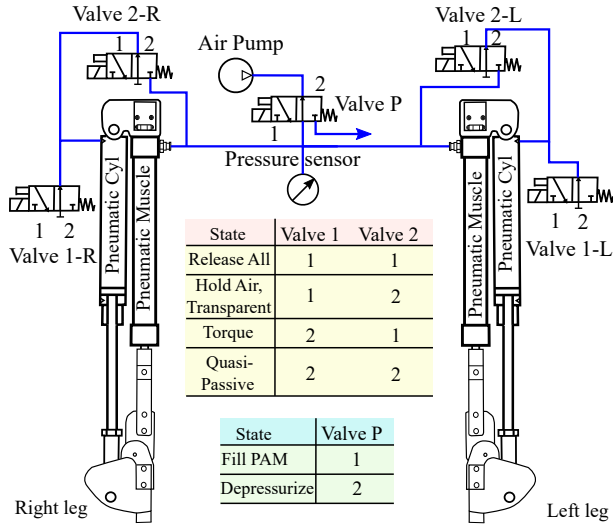


Fig. 2. Pneumatic circuit of the JSI-KneExo. Different valve positions achieve different exoskeleton states.

Transparent,” involves the air pump filling the PAM to the desired pressure set in the control algorithm, but valve 1 has a clutch function, meaning that if in position ‘1’ the pneumatic cylinder appears transparent as the chamber is connected to the atmosphere and air cannot be compressed. After being in the transparent state, by setting valve 2 to ‘1’, compressed air enters the cylinder chamber, producing force and joint torque. It’s crucial to revert valve 1 to ‘2’ to prevent air discharge. This state is called “Torque” or active mode. The last state is the “Quasi-passive”, in which both valves are set to position ‘2’. Torque is generated as the air inside the cylinder is compressed by knee flexion, acting as a nonlinear progressive compression spring resisting rotation. Furthermore, in this state, compressed air can be returned to the PAM by flexing the joint and switching valve 2 to ‘1’ so that air flows back into the PAM.

C. Mathematical model

1) *Air pump*: The air pump has the function of charging the PAM with compressed air to the desired pressure. Commercially available air pumps are rated for no-load air flow at 0 bar pressure. Therefore, it is hard to calculate the time required to fill the PAM as the pressure increases. Another approach involves experimentally identifying the pressure-time profile. Hence, two air pumps were experimentally identified and compared: BD-04A-20L (maximum pressure: 3.32 bar, 20 L/min flow rate at 0 bar) and the air piston pump BD-07A-35L (maximum pressure: 6.5 bar, 35 L/min flow rate at 0 bar). Fig. 3 depicts the measured pressure-time profile when filling the pneumatic muscle DMSP-20-100N-RM-RM for both pumps. The measured data were fitted with the following exponential function:

$$p_m(t) = p_{\max}(1 - e^{-t/k}), \quad (1)$$

where $p_m(t)$ is the actual pressure at time t , p_{\max} is the max. nominal pressure for the pump, and k is the pump constant

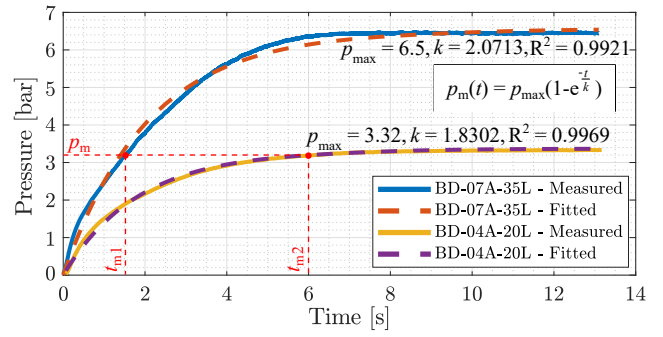


Fig. 3. Filling compressed air into the PAM with two different pumps, the larger BD-07A-35L and the smaller BD-04A-20L. The equation fitted through measured data has the form: $p_m(t) = p_{\max}(1 - e^{-t/k})$. For the larger pump: $p_{\max} = 6.5$ bar, $k = 2.0713$, and $R^2 = 0.9921$. For the smaller pump: $p_{\max} = 3.32$ bar, $k = 1.8302$ and $R^2 = 0.9969$.

identified for both pumps. The coefficient of determination is $R^2 = 0.9921$ for BD-07A-35L and $R^2 = 0.9969$ for BD-04A-20L. The time t_m required to reach the desired pressure p_m in the PAM can now be determined using Eq. (1).

2) *Pneumatic Artificial Muscle (PAM)*: When the air gets compressed inside the PAM, its length L_m and volume V_m change. The analytical dependency $V_m(L_m)$ is known and adopted from [24]. However, with a known PAM pressure p_m its length L_m can only be estimated from the FESTO datasheet for the exact PAM or other existing PAM models [24], [25]. Since FESTO does not provide an analytical model, the PAM model was determined experimentally. The dependency between the pressure p_m , length L_m , and the volume V_m is needed to compute the actuator’s torque. Therefore, the model was determined experimentally by compressing air into the PAM and measuring the contraction ε . The PAM force was zero during the identification as the linear bearing allows unrestrained contraction.

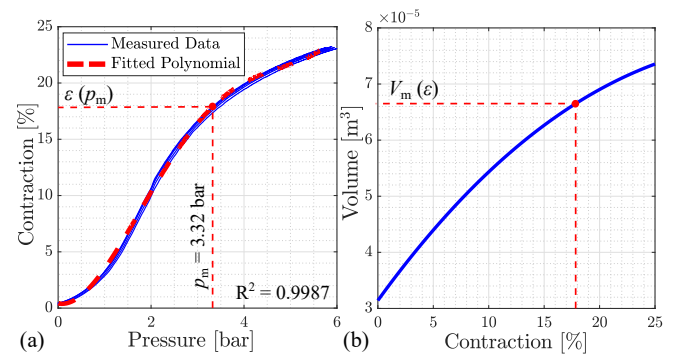


Fig. 4. Model-identification of the PAM DMSP-20-100N-RM-RM. In (a) PAM contraction versus pressure. In (b) PAM volume versus contraction.

The experimental identification is shown in Fig. 4, where (a) shows the measured contraction ε as a function of PAM pressure p_m , and (b) shows the analytical model linking PAM volume V_m and contraction ε , given in Eq. 3, for different contractions where the maximum contraction for the chosen PAM is equal to 25%. The measured data were fitted with a

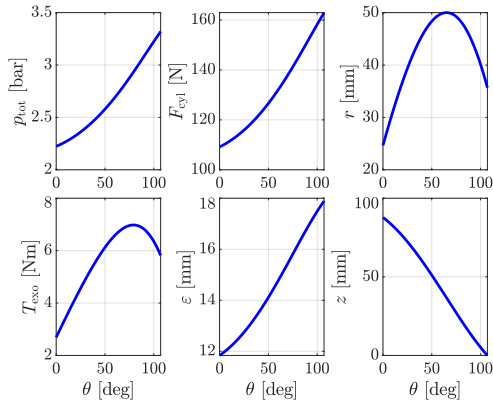


Fig. 6. Theoretical profiles of different physical parameters for the joint rotation from $\theta = 107^\circ$ to $\theta = 0^\circ$.

than in the active mode. Still, the air can be returned back into the PAM by setting valve 2 in position '1' once the air has been compressed in the cylinder (person sitting). The mathematical model in this paper doesn't account for PAM stretching that occurs beyond $\theta = 107^\circ$, even though rotation can reach $\theta = 135^\circ$. Experimental results will assess the exoskeleton's overall dynamics.

III. THE JSI-KNEEXO EVALUATION

This section presents a pilot study with an able-bodied subject (27 years old, 90 kg, 1.93 m tall), aiming to validate JSI-KneExo's key contributions. The exoskeleton was controlled in Simulink Real-Time™, while the pressure, angle, and force data were collected and analyzed offline in Matlab. The experimental setup is in Fig. 7. To determine exoskeleton impact on the subject, a multi-channel Trigno wireless EMG system (Delsys, USA) recorded Vastus Medialis (V. Med.) and Gluteus Maximus (Glut. M.) muscle activity at 2148.15 Hz, following SENIAM guidelines [26]. Prior to experiments, muscle maximum voluntary contractions (MVC) were recorded. Optitrack's 16 cameras (NaturalPoint, USA) at 120 Hz captured joint kinematics. Using 37 markers as per Motive Optical motion capture software, the human skeleton was reconstructed. Visual feedback on a screen ensured subject positioning consistency for repeatable experiments.

A. Experiment

The subject was instructed to perform ten sit-to-stand and stand-to-sit transitions under unassisted (transparent) and assisted conditions. The experiment aims to validate the energy recovery (compressed air return to PAM) while relieving the leg muscles, and to evaluate the exoskeleton operation, highlighting the transparency achieved after every sit-down while storing recovered air. When standing up, the exoskeleton assisted the subject in active mode, and when sitting down, the exoskeleton assisted the subject in quasi-passive mode. In the unassisted trial, the state was set to "Release All" to enable entire transparency.

Strategy and Control: The controller for the assisted condition involves a state machine with states triggered based on threshold values from a pressure sensor and two encoders,

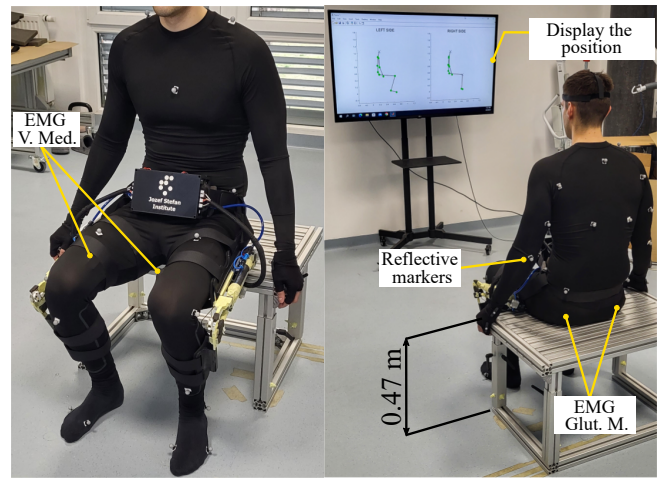


Fig. 7. Experimental setup: EMG electrodes, reflective markers, and screen for visual feedback.

with knee angular velocity derived through knee angle numerical differentiation. Exoskeleton torque was computed offline by multiplying the cylinder force with the lever arm length, calculated from the knee angle and mathematical model. In Fig. 8, the average exoskeleton torque (right leg) and its standard deviation across ten repetitions are presented in relation to the transition, with 100% denoting sitting and 0% indicating standing. Figure 9 shows the pressure change in both PAMs simultaneously, since the pressure sensor is connected to both PAMs (see Fig. 2). The intervals when the pump was switched on and off are indicated, as well as the amount of recovered air. In both figures, the exoskeleton

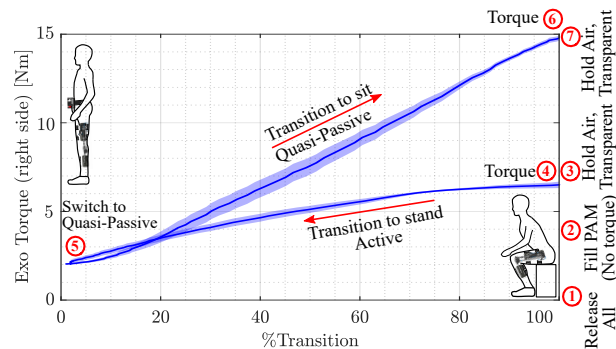


Fig. 8. Right leg exoskeleton torque during transition, scaled from 100% (sitting) to 0% (standing), with numbered circles indicating different states.

states are indicated by numbers. The experiment is divided into seven parts as follows.

Initial Sitting: The experiment started by equalizing the actuator to atmospheric pressure in ①. The air pump gradually filled the PAM to a set pressure of 3.2 bar in ②. In ③ the air pump was switched off as the PAM was charged with compressed air but had not yet been released into the cylinder and therefore the exoskeleton was still transparent.

Standing Up: In ④, the sensors detected the subject's standing up movement, thus the actuator released the compressed air into the pneumatic cylinder, providing an active

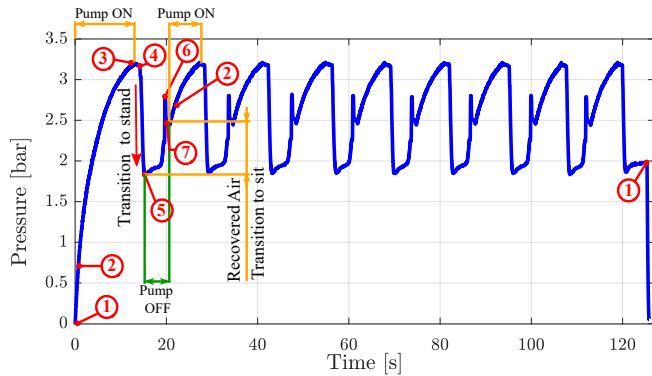


Fig. 9. Pressure sensor measurements over time with state distinctions using numbers. Pump on-off intervals and air recovery periods are marked.

torque of ~ 6.7 Nm which gradually decreased as the pressure dropped until ⑤ (fully standing), at which point the pressure was equal to ~ 1.85 bar and the torque ~ 2 Nm.

Sitting Down: Upon sensor detection of the standing position, the mode was changed to "Quasi-passive". Thus, from ⑤ to ⑥, when the subject transitioned to sitting, the air was compressed exclusively in the pneumatic cylinder, reaching a maximum torque of ~ 14.88 Nm.

Air Return: By detecting the subjects' full seating in ⑥, and by positioning valve 2 to '1', compressed air from the cylinder had flown back to the PAM, restoring the PAM pressure from ~ 1.85 bar to ~ 2.5 bar, as the subject went from standing to sitting while the air pump was off.

Transparent Sitting: In ⑦, "Hold Air, Transparent" state holds the remaining air in the PAM but releases the compressed air from the cylinder allowing unobstructed sitting.

Next Repetition: In the next repetition, the air pump only had to compensate for air loss, as the joint hadn't fully rotated to its end position. Thus, the air pump has been restarted (state ②), which allowed compensation for the pressure difference in the PAM up to 3.2 bar.

End: Finally, all the compressed air from the actuator was released in ① and the experiment was completed.

IV. DISCUSSION

This section discusses the energy recovery of the exoskeleton with the simultaneous muscle activity reduction in sitting transfers. Fig. 10 displays average muscle activity over ten repetitions for transitions between sitting and standing, comparing unassisted (ExoOff) and assisted (ExoOn) conditions. The mean envelope of the raw EMG signals was extracted to analyze muscle effort, involving a series of filtering steps: 4th order bandpass Butterworth (20-400 Hz), rectification, and low pass filtering (5 Hz, 4th order Butterworth). EMG amplitude was normalized to the subject's MVC, segmented, and averaged based on %Sitting and %Standing identified from the knee angle. **EMG reduction with simultaneous energy recovery:** Interestingly, returning compressed air to the exoskeleton reservoir not only saved energy and pumping time but also reduced muscular effort. Notably, V. Med. activity decreased by $\sim 31\%$ (mean effort) when sitting down

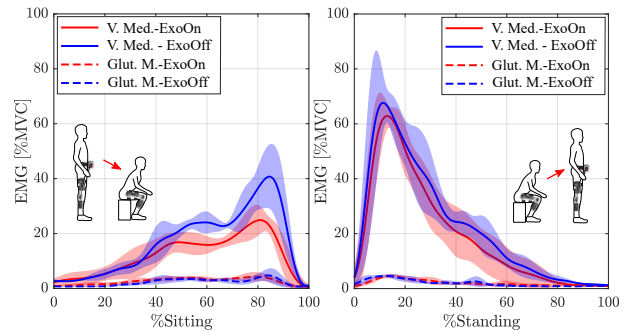


Fig. 10. EMG recordings of the vastus medialis and gluteus maximus during sitting and standing transfers under assisted and unassisted conditions.

with assistance compared to unassisted. Glut. M. showed no major changes between the conditions, with low activity normalized to MVC. During standing up, a mean effort was reduced by $\sim 13\%$ in V. Med. when the exoskeleton assisted.

Actuation frequency relies on the air pump and the desired pressure, set at 3.2 bar during experimentation. To assess energy recovery usefulness, three states with specific pressures are highlighted: state ③ at 3.2 bar, state ⑤ at 1.85 ± 0.01 bar, and state ⑦ at 2.46 ± 0.01 bar. With energy recovery, the air pump has to refill only from 2.46 ± 0.01 up to 3.2 bar. Without energy recovery, the air pump has to refill from the residual PAM pressure after actuation, 1.85 ± 0.01 , up to 3.2 bar. The time to restore pressure to the desired level is determined using Eq. (1), derived earlier from air pump characterization. The results are listed in the following table.

TABLE I
MAX. ACTUATION FREQUENCY W/ AND W/O ENERGY RECOVERY

	Air pump: BD-04A-20L	Air pump: BD-07A-35L
Max. Freq. w/ ER ¹	$8.32 \pm 0.04 \text{ min}^{-1}$	$71.53 \pm 0.66 \text{ min}^{-1}$
Max. Freq. w/o ER ²	$6.55 \pm 0.02 \text{ min}^{-1}$	$43.31 \pm 0.34 \text{ min}^{-1}$

¹ Time to restore pressure with BD-04A-20L: 3.61 ± 0.02 s (1 leg), 7.21 ± 0.03 s (both legs). With BD-07A-35L: 0.42 ± 0 s (1 leg), 0.84 ± 0.01 s (both)

² Time to restore pressure with BD-04A-20L: 4.58 ± 0.02 s (1 leg), 9.16 ± 0.03 s (both legs). With BD-07A-35L: 0.71 ± 0.01 s (1 leg), 1.42 ± 0.01 s (both)

Yet, this frequency is derived from the air pump's ability. In experiments, the frequency, of course, is also influenced by the user's pace and transfer intervals. When pumping intervals are translated into energy savings through recovery, the exoskeleton's battery endurance extends by 1.27 ± 0.01 , $\sim 27\%$ (small pump), or 1.69 ± 0.02 , $\sim 69\%$ (large pump).

V. CONCLUSION

In conclusion, the key innovation of the JSI-KneExo is simultaneous human assistance with efficient energy recovery, leading to approximately $\sim 27\%$ energy savings as the pump only needs to recompensate part of the compressed air. This is enabled by a novel pneumatic circuit design that provides different operation modes, and portable pneumatic actuation using PAM as an air tank. However, this paper presents only initial results from a single subject and lacks statistical evidence. Future endeavors will analyze the effects on a larger sample of subjects.

REFERENCES

- [1] J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: Generating electricity during walking with minimal user effort," *Science*, vol. 319, no. 5864, pp. 807–810, 2008.
- [2] X. Wu, W. Cao, H. Yu, Z. Zhang, Y. Leng, and M. Zhang, "Generating Electricity During Locomotion Modes Dominated by Negative Work via a Knee Energy-Harvesting Exoskeleton," pp. 1–11, 2022.
- [3] B. Laschowski, J. McPhee, and J. Andrysek, "Lower-Limb Prostheses and Exoskeletons With Energy Regeneration: Mechatronic Design and Optimization Review," *Journal of Mechanisms and Robotics*, vol. 11, no. 4, pp. 1–43, 2019.
- [4] A. M. Dollar and H. Herr, "Design of a quasi-passive knee exoskeleton to assist running," *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, pp. 747–754, 2008.
- [5] R. W. Nuckols, K. Z. Takahashi, D. J. Farris, S. Mizrahi, R. Riemer, and G. S. Sawicki, "Mechanics of walking and running up and downhill: A joint-level perspective to guide design of lower-limb exoskeletons," *PLoS ONE*, vol. 15, no. 8 August, pp. 1–20, 2020.
- [6] B. Laschowski, R. S. Razavian, and J. McPhee, "Simulation of Stand-to-Sit Biomechanics for Robotic Exoskeletons and Prostheses with Energy Regeneration," *IEEE Transactions on Medical Robotics and Bionics*, vol. 3, no. 2, pp. 455–462, 2021.
- [7] Donald A. Neumann, "Kinesiology of the Musculoskeletal System Foundations for Rehabilitation". Elsevier, 2016.
- [8] K. Schmidt, J. E. Duarte, M. Grimmer, A. Sancho-Puchades, H. Wei, C. S. Easthope, and R. Riener, "The myosuit: Bi-articular anti-gravity exosuit that reduces hip extensor activity in sitting transfers," *Frontiers in Neurobotics*, vol. 11, no. OCT, pp. 1–16, 2017.
- [9] M. K. Shepherd and E. J. Rouse, "Design and Validation of a Torque-Controllable Knee Exoskeleton for Sit-to-Stand Assistance," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 4, pp. 1695–1704, 2017.
- [10] L. Liu, Z. Hong, B. Penzlin, B. J. Misgeld, C. Ngo, L. Bergmann, and S. Leonhardt, "Low Impedance-Guaranteed Gain-Scheduled GESO for Torque-Controlled VSA with Application of Exoskeleton-Assisted Sit-to-Stand," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 4, pp. 2080–2091, 2021.
- [11] H. Zhu, C. Nesler, N. Divekar, V. Peddinti, and R. D. Gregg, "Design Principles for Compact, Backdrivable Actuation in Partial-Assist Powered Knee Orthoses," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 6, pp. 3104–3115, 2021.
- [12] J. Vantilt, K. Tanghe, M. Afschrift, A. K. Bruijnes, K. Junius, J. Geeroms, E. Aertbeliën, F. De Groote, D. Lefeber, I. Jonkers, and J. De Schutter, "Model-based control for exoskeletons with series elastic actuators evaluated on sit-to-stand movements," *Journal of NeuroEngineering and Rehabilitation*, vol. 16, no. 1, pp. 1–21, 2019.
- [13] S. H. Collins, M. Bruce Wiggin, and G. S. Sawicki, "Reducing the energy cost of human walking using an unpowered exoskeleton," *Nature*, vol. 522, no. 7555, pp. 212–215, 2015.
- [14] C. Di Natali, A. Sadeghi, A. Mondini, E. Bottenberg, B. Hartigan, A. De Eyto, L. O'Sullivan, E. Rocon, K. Stadler, B. Mazzolai, D. G. Caldwell, and J. Ortiz, "Pneumatic Quasi-Passive Actuation for Soft Assistive Lower Limbs Exoskeleton," *Frontiers in Neurobotics*, vol. 14, no. June, pp. 1–18, 2020.
- [15] L. Miskovic, M. Dezman, and T. Petric, "Pneumatic Quasi-Passive Variable Stiffness Mechanism for Energy Storage Applications," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 1705–1712, 2022.
- [16] S. Kumar, M. R. Zwall, E. A. Bolivar-Nieto, R. D. Gregg, and N. Gans, "Extremum Seeking Control for Stiffness Auto-Tuning of a Quasi-Passive Ankle Exoskeleton," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4604–4611, 2020.
- [17] A. Sutrisno and D. J. Braun, "Enhancing Mobility with Quasi-Passive Variable Stiffness Exoskeletons," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 3, pp. 487–496, 2019.
- [18] C. J. Walsh, K. Endo, and H. Herr, "A quasi-passive leg exoskeleton for load-carrying augmentation," *International Journal of Humanoid Robotics*, vol. 4, no. 3, pp. 487–506, 2007.
- [19] D. Maeda, K. Tominaga, T. Oku, H. T. Pham, S. Saeki, M. Uemura, H. Hirai, and F. Miyazaki, "Muscle synergy analysis of human adaptation to a variable-stiffness exoskeleton: Human walk with a knee exoskeleton with pneumatic artificial muscles," *IEEE-RAS International Conference on Humanoid Robots*, no. 1, pp. 638–644, 2012.
- [20] K. Knaepen, P. Beyl, S. Duerinck, F. Hagman, D. Lefeber, and R. Meeusen, "Human-robot interaction: Kinematics and muscle activity inside a powered compliant knee exoskeleton," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 6, pp. 1128–1137, 2014.
- [21] L. Miskovic, M. Dezman, and T. Petric, "Pneumatic Exoskeleton Joint with a Self-Supporting Air Tank and Stiffness Modulation: Design, Modeling, and Experimental Evaluation," *IEEE/ASME Transactions on Mechatronics*, pp. 1–12, 2024.
- [22] M. Wehner, B. Quinlivan, P. M. Aubin, E. Martinez-Villalpando, M. Baumann, L. Stirling, K. Holt, R. Wood, and C. Walsh, "A lightweight soft exosuit for gait assistance," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 3362–3369, 2013.
- [23] U. Heo, S. J. Kim, and J. Kim, "Backdrivable and Fully-Portable Pneumatic Back Support Exoskeleton for Lifting Assistance," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2047–2053, 2020.
- [24] M. Martens and I. Boblan, "Modeling the static force of a Festo pneumatic muscle actuator: A new approach and a comparison to existing models," *Actuators*, vol. 6, no. 4, pp. 1–11, 2017.
- [25] C. P. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Transactions on Robotics and Automation*, vol. 12, no. 1, pp. 90–102, 1996.
- [26] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, and G. Rau, "Development of recommendations for SEMG sensors and sensor placement procedures," *J. Electromyogr. Kinesiol.*, vol. 10, no. 5, p. 361–374, 2000.