Mechanisms and Machine Science

Maria Cristina Valigi
Giovanni Boschetti
Carmen Visconte
Sergio Savino *Editors*

# Advances in Italian Mechanism Science

## Proceedings of the 6th International Conference of IFToMM Italy - Volume 2

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Maria Cristina Valigi · Giovanni Boschetti ·
Carmen Visconte · Sergio Savino
Editors

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# Preface

These two proceeding books collect the papers accepted for presentation at the Sixth International Conference of IFToMM Italy, IFIT 2026. The conference, which originates in the IFToMM Italy community and its international network, aims to bring together researchers, industry experts, and students from a wide variety of fields related to Mechanism and Machine Science (MMS) in a collaborative and engaging context, in order to foster the exchange of information and encourage collaboration.

The Sixth International Conference of IFToMM Italy was held on September 9–11, 2026, in Foligno (Perugia), Italy, in a branch campus of University of Perugia. The conference received the patronage of IFToMM, the International Federation for the Promotion of Mechanism and Machine Science, of University of Perugia, of City of Foligno, of Association Study Center City of Foligno, and of the Association of Engineers of the Province of Perugia. It was also supported by the IFToMM Permanent Commission for the History of Mechanism and Machine Science, the IFToMM Technical Committee for Sustainable Energy Systems, the IFToMM Technical Committee for Robotics and Mechatronics, the IFToMM Technical Committee for Linkages and Mechanical Control, the IFToMM Cross Disciplinary Group 1: Securing our future environment, the IFToMM Technical Committee for Tribology, and the IFToMM Member Organizations for Germany, Japan, Portugal & Spain.

IFToMM was officially founded on September 29, 1969, during the Second World Congress on Theory of Machines and Mechanisms in Zakopane, Poland. Italy was among the 13 founding member nations, and the Italian researchers played a pivotal role in shaping the federation right from the start. IFToMM Italy was founded in 1970 and has been a very active member since then.

The Sixth International Conference of IFToMM Italy continues a series of IFIT conferences that was started in 2016 by IFToMM Italy in Vicenza. The second event was held in Cassino in 2018, while the third event was successfully hosted online in 2020 due to the global circumstances and restrictions of the COVID-19 pandemic. The fourth edition was held in Naples in 2022, followed by a fifth edition hosted in Turin in 2024. The sixth edition of the conference confirmed the growth of the research community, reaching 130 presented papers, the highest number in IFIT history. All papers have been selected through an accurate peer-review process, which have ensured their relevance, novelty, and clarity.

Due to the high number of submissions, the proceedings are published in two volumes.

This second volume is divided into 9 chapters:

- Adaptive and Assistive Robotic Gripping.
- Collaborative robotics and human-robot interaction.
- Dynamics of Machinery and multiphysics modeling.
- Robotics.
- Mobile Robotics.

The conference includes three Special Sessions managed by Chairpersons, who proposed and promoted their topics, collected the related papers, and chaired the corresponding conference sessions. This allowed enriching the conference with subjects representing the ultimate frontier of research.

We are grateful to the chairpersons who promoted the special sessions:

- Andrea Botta and Teresa Sinico, Robotics for Unstructured and Challenging Environments.
- Sergio Savino and Giulia Morettini, Advanced Technologies for Ground and Space Mobility Applications.
- Lorenza Mattei and Silvia Logozzo, Tribology for Life and Sustainability: From Biotribology to Green Engineering.

We would like to thank all the members of the Scientific and Organizing Committees for their strong contribution toward the success of IFIT 2026:

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We extend our deepest appreciation to the authors and reviewers for their outstanding contributions and timely feedback, which were instrumental in ensuring the high scientific standards of IFIT 2026. We are also grateful to the IFToMM Italy association for coordinating the conference organization as well as to the IFToMM federation and the Permanent Commission and Technical Committees for their patronage of IFIT 2026. Finally, we thank all the staff members at Springer for their valuable editorial support.

We believe researchers in Mechanism and Machine Science will find these volumes an invaluable and current resource for the newest discoveries in the field.

June 2026

Maria Cristina Valigi
Giovanni Boschetti
Carmen Visconte
Sergio Savino

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# Adaptive and Assistive Robotic Gripping



# Data-Driven Tracking of Wrist Motions for a Soft Exoskeleton Based on Twisted String Actuators

Callista Shekar Ayu Supriyono[1,2], Mihai Dragusanu[1(✉)], Muhammad Innamul Hasan[1], and Monica Malvezzi[1]

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**Abstract.** This paper presents experimental testing of a Twisted String Actuator (TSA)-based wrist exoskeleton integrating a data-driven feedforward command estimator within a position-tracking control architecture, for rehabilitation applications. The device has three degrees of freedom (DOF), allowing for flexion/extension, abduction/adduction, and pronation/supination motions through the coordinated actuation of four motors. The exoskeleton structure is lightweight and compliant. Given the nonlinear transmission ratio of TSA and the user's specific tendon routing characteristics, a data driven feedforward command estimator is implemented. Three regression models are trained to map desired joint angle trajectories to motor commands: a Multilayer Perceptron (MLP), a Feedforward Neural Network (FFNN), and a Gradient Boosted Tree ensemble (XGBoost). All models share a ten-dimensional input vector combining kinematic features and autoregressive motor state, achieving $R^2 > 0.996$ across all motors on the held-out test set. Experimental validation across 120 trials covering all six wrist movement directions confirms autonomous trajectory replay with mean RMSE below 2.6°, without requiring continuous IMU feedback during the replay phase. The results demonstrate that integrating AI with TSA actuation is a viable strategy for accurate, continuous-sensor-free replay for wrist rehabilitation exoskeletons.

**Keywords:** Wearable robots · Exoskeleton · Robotic rehabilitation · Twisted String Actuators · Artificial intelligence

## 1 Introduction

Wearable robotic exoskeletons have emerged as a key technology in rehabilitation and assistive robotics, particularly for upper-limb motor recovery. Their capac-

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ity to deliver repetitive, controlled, and task-specific motion has positioned them as an effective tool in the treatment of neurological impairments such as stroke and spinal cord injury. Concurrent advances in lightweight materials, embedded systems, and sensing technologies have further enabled the development of compact, portable, and user-oriented devices, accelerating their translation from laboratory settings to real-world applications [1–3].

Wearable robotic exoskeletons are undergoing a shift from conventional control strategies toward intelligent, data-driven approaches. Classical controllers, typically based on predefined trajectories or impedance control, are inherently limited in their ability to adapt to the variability of users' characteristics and dynamic user conditions. As a result, recent research has increasingly focused on the integration of Artificial Intelligence (AI) and Machine Learning to enhance adaptability, personalization, and performance. These approaches can manage complex nonlinear relationships between user intent, actuator inputs, and resulting motion. However, they often rely on extensive sensor feedback, such as inertial measurement units (IMUs) or Electromyography (EMG), which introduces additional hardware complexity and increases system cost [4].

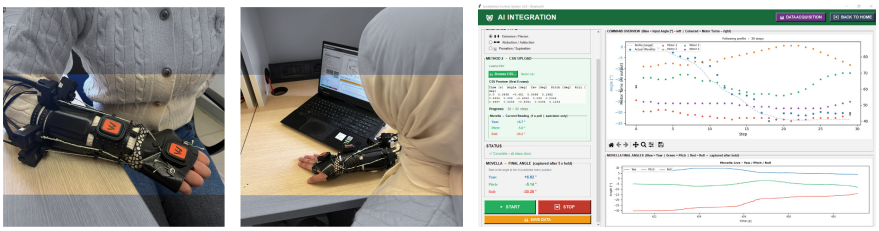
From the device design point of view, there is growing interest in alternative actuation mechanisms that can meet the strict requirements of wearable systems in terms of weight, efficiency, and compactness. Twisted String Actuators (TSAs) represent a particularly promising solution, as they provide high force-to-weight ratios and simple mechanical architectures by converting rotational motion into linear contraction through string twisting. Despite these advantages, the adoption of TSAs in exoskeleton systems remains limited when compared to more established solutions such as rigid-link transmissions or cable-driven mechanisms [5]. Existing works predominantly address TSA modeling, characterization, and conventional control on wearable devices [6–11]. In [6] a 3-DOF lightweight TSA-based wrist exoskeleton has been proposed with IMU-based angle tracking and a demonstration-based "learning mode," in which a therapist guides the patient's motion and the system subsequently reproduces the recorded trajectory. Another 3-DOF flexible wrist exoskeleton has been developed using inertial sensing for motion tracking and rehabilitation purposes in [7]. Beyond wrist-focused systems, TSAs have been integrated into assistive wearable devices such as fabric-based gloves designed to enhance grip strength and reduce muscle fatigue during manual tasks, showing measurable reductions in muscular effort without restricting user motion [9]. Soft wearable robotic systems employing adjustable TSA mechanisms and multi-stage transmissions have demonstrated significant reductions in muscle activation during load-handling activities [10]. In rehabilitation-oriented designs, TSA-based assistive gloves such as MGlove-TS have been developed to support grasping and daily activities, emphasizing portability, flexibility, and user comfort [11]. While these highlight the versatility and effectiveness of TSAs in wearable robotics, their control strategies remain largely based on predefined motion reproduction, continuous sensor feedback, or classical control approaches. They do not leverage data-driven models to learn the intrinsic nonlinear behavior of TSAs for generalized motion control, nor

do they address the possibility of reducing or eliminating reliance on external sensors. Only a limited number of studies applied AI techniques in TSA-based devices [12]. Although these contributions demonstrate the potential of AI in TSA-related applications, they do not address the problem of motion control in multi-DOF wearable exoskeletons, nor do they explore the use of learned models for sensor-independent positioning.

This work presents a study combining a TSA-based actuation system with an AI-driven control strategy for a improved version of the 3-DOF wrist exoskeleton presented in [6]. Motion data for system training, testing and validation are acquired using two inertial sensors measuring joint orientation (yaw, pitch, roll), and actuator rotation angle. Through structured exercises spanning the full range of motion, a comprehensive dataset is constructed to model the relationship between actuator inputs and resulting joint kinematics. The objective is to define an AI-based system to learn this mapping and ultimately eliminate the need for continuous external sensing, enabling accurate, external-sensor-independent control of the exoskeleton. This approach reduces system complexity and opens new directions for the integration of lightweight actuators and intelligent control in wearable robotics. It is worth noting that the AI model is trained and validated on a single subject, and the home-position calibration is inherently user-specific, generalization to multiple users will be addressed in future work.

## 2 Prototype

***Wrist Exoskeleton Design.*** The proposed wrist exoskeleton (Fig. 1c) is a lightweight, portable, and compliant assistive device that prioritizes both functionality and user comfort. The structure of the exoskeleton is soft, allowing it to closely conform to the anatomical structure of the user's hand and wrist, improving wearability and reducing discomfort during prolonged use. Thermoplastic polyurethane (TPU) is selected as the primary structural material, because it has suitable mechanical properties, including flexibility, durability, and ability to provide a comfortable interface between the device and the human body. The exoskeleton is specifically intended for rehabilitation and training applications, targeting individuals with limited active control of the wrist and hand, such as




(a) (b) (c)

**Fig. 1.** Wrist exoskeleton: (a) worn by user; (b) testing environment; (c) the GUI.

those recovering from neurological or musculoskeletal impairments. To achieve a compact and efficient design, the system employs a minimal actuation strategy consisting of four motors, which are carefully coordinated to produce 3-DOF and enabling flexion/extension, abduction/adduction, and pronation/supination motions. Tendon actuation is realized through TSA, where rotational motion from the motors is converted into linear contraction through the twisting of strings. To enable motion tracking for collecting the data for AI-based tracking system definition, the device is equipped with two Movella DOT IMU sensors, positioned on the forearm and the hand to capture relative motion between segments. Wireless communication is enabled by an RN42 Bluetooth module, ensuring reliable data transmission, while overall system control is managed by an OpenCM9.04 microcontroller board. The exoskeleton mechanical design incorporates adjustable interruption pins that can be repositioned to modify the effective twisting zone of the TSA mechanism; this feature allows the adaptation to different user requirements, ranges of motion, and rehabilitation protocols.

***Control System Implementation.*** The control system of the proposed wrist exoskeleton is implemented using a Graphical User Interface (GUI), Fig. 1c. Commands generated from the GUI are wirelessly transmitted to the exoskeleton using Bluetooth communication. The OpenCM 9.04 is responsible for managing the actuation of each TSA, ensuring coordinated motor operation based on the received commands. Two main control implementations are developed within the system architecture. The first is dedicated to data acquisition for AI training, which is described in this subsection, while the second, involving AI-based control after model deployment, will be discussed in a subsequent section. In the data acquisition phase, the angle-based control is provided. The angle-based control mode utilizes feedback from the IMU sensors to achieve closed-loop control based on the algorithm presented in [13]. In this mode, the user first selects the desired movement category, after which a target angle is specified through the GUI. This target is transmitted to the microcontroller as the desired final position. During operation, the IMU continuously measures the current wrist angle and sends this information to the controller. Based on the difference between the current angle and the target angle, the microcontroller commands the motors to rotate accordingly. The motors continue to actuate the TSA mechanism until the desired angle is reached, at which point motor movement is stopped. At the motor level, each Dynamixel actuator is governed by an onboard position controller. The data-driven estimator, described in the following section, operates above this layer, predicting motor tick commands that approximate the inverse of the nonlinear TSA transmission.

## 3 AI Training and Test

***Data Acquisition.*** Data acquisition was conducted to capture representative motion patterns across all three DOFs of the wrist, namely flexion/extension, abduction/adduction, and pronation/supination. An initial calibration step was performed by setting the pre-twist condition of the TSA and determining the

user-specific home position. This home position varies between users and is established by manually adjusting the string contraction of each motor until a neutral and comfortable wrist posture is achieved, which is then defined as 0°. Following calibration, data collection was performed using the angle-based control mode through the GUI. Target angles were incrementally specified starting from the home position, beginning at 5° and increasing in steps of 5° (e.g., −10°, −15°, and so on) until the maximum range of motion of the user was reached. A similar procedure was conducted in the negative direction (e.g., −5°, −10°, etc.) to capture movements in the opposite direction. This bidirectional data collection is necessary because different wrist movements exhibit different directional conventions, for example, certain motions such as extension, adduction, and pronation may correspond to decreasing angle values relative to the home position, while others correspond to increasing values.

All acquired data were stored in a structured CSV file format for subsequent analysis and AI training. Each data entry includes the initial motor tick values at the home position, the duration of the movement, the time-series evolution of the wrist angle, and the corresponding tick values of all four motors throughout the motion. In addition, the dataset also records the orientation information from the IMU, including yaw, pitch, and roll angles, providing a more comprehensive representation of wrist kinematics. This dataset serves as the foundation for training the AI model, enabling it to learn the relationship between motor actuation patterns and resulting wrist movements.

The resulting dataset comprised 75 CSV files totalling 2,151 samples across three movement categories: flexion/extension (910 samples, 33 files), pronation/supination (789 samples, 26 files), and abduction/adduction (452 samples, 16 files). Each movement direction was recorded at target angles ranging from 50° to 5° in 50° increments, with two sessions per angle. Each file corresponds to a single movement direction at a specific target angle, larger angles yield longer trajectories and more samples. Data were logged at 10 Hz.

**Table 1.** Per-motor regression performance on the held-out test set.

| Model | Overall | Motor 1 | | Motor 2 | | Motor 3 | | Motor 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | $R^2$ | MAE | $R^2$ | MAE | $R^2$ | MAE | $R^2$ | MAE |
| MLP | 0.9967 | 0.997 | 0.36 | 0.996 | 0.51 | 0.997 | 0.50 | 0.996 | 0.34 |
| FFNN | 0.9978 | 0.998 | 0.31 | 0.998 | 0.36 | 0.998 | 0.42 | 0.996 | 0.32 |
| XGBoost | 0.9972 | 0.996 | 0.31 | 0.998 | 0.30 | 0.999 | 0.27 | 0.997 | 0.28 |

MAE values in encoder turns.

***Training and Testing.*** Three regression models (Fig. 2) were trained to map a desired joint angle and current motor state to four motor turn commands: a Multilayer Perceptron (MLP) (scikit-learn), a Feedforward Neural Network (FFNN)(PyTorch), and a Gradient Boosted Tree ensemble (XGBoost). Each of the movement directions is produced through coordinated actuation of all four

motors, where specific combinations of twisting and untwisting actions generate the desired wrist motion. Flexion is achieved when motors M2 and M3 twist while M1 and M4 untwist, adduction when M1 and M2 twist while M3 and M4 untwist, and pronation when M2 and M4 twist while M1 and M3 untwist, with the reverse coordination producing the antagonist motion in each case. The regression therefore predicts all motor commands simultaneously at each time step, with the "per motor" $R^2$ and MAE metrics reported in Table 1 reflecting the accuracy of individual output within joint prediction. All models share the same ten-dimensional input vector: current joint angle, first- and second-order angle differences, a 3-sample rolling mean and standard deviation, a movement-type label (0–5), and the four lag-one motor tick values. Data were split 80/20 at the file level using `GroupShuffleSplit` to prevent leakage between sessions.

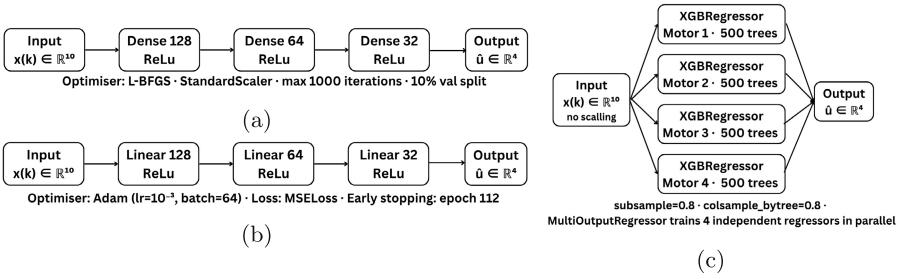



**Fig. 2.** Architecture diagrams of the three regression models: (a) MLP (scikit-learn), L-BFGS optimiser; (b) FFNN (PyTorch), Adam optimiser with early stopping; (c) XGBoost, four independent `XGBRegressor` ensembles via `MultiOutputRegressor`.

The MLP uses three fully connected layers ($128 \to 64 \to 32$, ReLU) trained with L-BFGS on standardised features. The FFNN is architecturally equivalent but trained with mini-batch Adam ($lr = 10^{-3}$, batch = 64, MSELoss) and explicit early stopping (patience = 20 epochs) on standardised features and targets. XGBoost trains four independent boosted tree ensembles (500 rounds, max depth 5, $lr = 0.05$) directly on raw features, no scaling required, and provides native feature importances.

The FFNN achieved the highest overall $R^2 = 0.9978$ and the lowest mean MAE (0.35 turns), followed by XGBoost with overall $R^2 = 0.9972$ (0.29 turns mean MAE) and the MLP with overall $R^2 = 0.9967$ (0.43 turns mean MAE). All three models exceeded $R^2 = 0.996$ across every individual motor, confirming that the feature engineering strategy particularly the inclusion of autoregressive lag features is the principal enabler of accurate prediction regardless of the underlying architecture. Since all three models achieved statistically comparable offline accuracy ($R^2 > 0.996$, MAE $< 0.5$ turns across all motors), the assignment of one model per movement axis, MLP for flexion/extension, FFNN for abduction/adduction, and XGBoost for pronation/supination was a deliberate validation strategy rather than a performance-driven selection. The goal was to

evaluate all three architectures under real physical operating conditions, including command latency, motor response, and hardware timing, rather than relying solely on held-out regression metrics. This approach also demonstrates that the proposed feature engineering strategy, and in particular the autoregressive lag features, is the principal driver of accuracy regardless of the underlying model architecture, a practically relevant finding for future implementers who may wish to substitute one model for another based on deployment constraints such as computational resources or interpretability requirements. The motor command formulation is given in Eq. (1).

**Table 2.** Mean RMSE for wrist exercises (°).

| Flex./Ext | Abd./Add. | Pron./Supin. |
|---|---|---|
| $2.26 \pm 0.43/2.06 \pm 0.56$ | $2.01 \pm 0.41/2.18 \pm 0.34$ | $2.17 \pm 1.33/2.51 \pm 1.12$ |

## 4 AI-Exoskeleton Integration Test

To validate the performance of the data-driven feedforward estimator integrated within the position-tracking control architecture on the physical exoskeleton, a structured protocol was designed covering all six wrist movement directions: flexion, extension, abduction, adduction, pronation, and supination, each repeated 20 times, yielding 120 trials in total. The protocol consisted of two phases.

In the profiling phase, a physiotherapist guided the user through each movement while the Movella DOT IMU recorded the resulting joint angle trajectory as a time-stamped sequence $\{\theta^*(k)\}_{k=1}^{N}$. This profile encodes the intended range of motion and velocity envelope of a clinically correct movement and serves as the reference input to the AI controller. During the subsequent autonomous replay phase, no IMU feedback is required. In the replay phase, the recorded profile was uploaded to the GUI and replayed autonomously. At each step $k$, the target angle $\theta^*(k)$ is read from the pre-recorded profile. From this signal, two kinematic difference features are derived: the first-order difference $\Delta\theta(k) = \theta^*(k) - \theta^*(k-1)$ and the second-order difference $\Delta^2\theta(k)$, which capture the instantaneous velocity and acceleration of the desired trajectory. To characterise the local trajectory context, a 3-sample rolling mean $\bar{\theta}(k)$ and standard deviation $\sigma_\theta(k)$ are also computed. A discrete movement-type label $m \in \{0, \ldots, 5\}$ identifies the active motion category (one per direction), and $\mathbf{u}(k-1) \in \Re^4$ denotes the lag-one motor tick vector, encoding the previous motor state. Together, these ten features are passed to the trained estimator to produce the motor command:

$$\hat{\mathbf{u}}(k) = f\big(\theta^*(k),\, \Delta\theta(k),\, \Delta^2\theta(k),\, \bar{\theta}(k),\, \sigma_\theta(k),\, m,\, \mathbf{u}(k-1)\big) \tag{1}$$

The command $\hat{\mathbf{u}}(k)$ was transmitted to the microcontroller, which drove the motors to the target position before advancing to the next profile step. Performance was quantified using the Root Mean Square Error (RMSE) between the

reference profile and the IMU-measured angle, computed independently for each trial and averaged over the 20 repetitions to yield mean ± standard deviation per movement direction.

## 5 Results

The AI controller was evaluated on the physical exoskeleton across all six wrist movement directions. Trajectory tracking results are presented in Fig. 3 and quantitative RMSE values are reported in Table 2. All movement directions achieved mean RMSE below 2.6°. The lowest error was for abduction ($2.01 \pm 0.41°$), reflecting the smooth monotonic shape of that profile. The highest variability occurred in supination ($2.51 \pm 1.12°$), attributable to coupled forearm rotation sensitivity to limb positioning. The results confirm that the proposed estimator successfully generalises from physiotherapist-guided profiles to autonomous replay across all wrist DOFs.

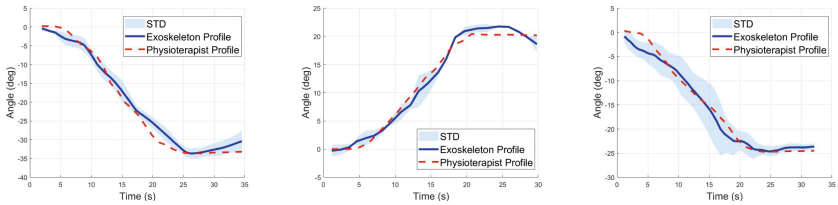



**Fig. 3.** Results of the AI Integration Exoskeleton by User: (a) flexion (with MLP Regressor), (b) adduction (with XG-Boost), and (c) supination (with Feed-forward). Red: reference trajectory, blue: average trajectory obtained from the twenty trials, light-blue band: standard deviation across the trials.

## 6 Discussion and Conclusion

This work presented an experimental validation of a data-driven feedforward command estimator integrated within a position-tracking control architecture, applied to a TSA-based wrist exoskeleton capable of 3-DOF. Three regression models: MLP, FFNN, and XGBoost were trained to map joint angle trajectories to motor commands, achieving $R^2 > 0.996$ across all motors and movement types, demonstrating that the proposed system, and particularly the inclusion of autoregressive lag features, is sufficient to capture the nonlinear kinematics of the TSA mechanism regardless of the underlying model.

Experimental validation across 120 trials confirmed that all six wrist movement directions could be replayed autonomously with mean RMSE below 2.6°, which is clinically acceptable for rehabilitation applications [14]. The smoothest

tracking was observed for abduction ($2.01 \pm 0.41°$), while the highest variability occurred in supination ($2.51 \pm 1.12°$), likely due to the sensitivity of forearm rotation to limb positioning. These results were achieved without any continuous external sensor feedback during replay, relying solely on the IMU-recorded reference profile and the learned motor model. The main contribution of this work is the integration of AI with TSA actuation in a multi-DOF wearable exoskeleton, an area that is still rather unexplored. By learning the intrinsic nonlinear behavior of the TSA mechanism directly from data, the proposed approach eliminates the need for continuous real-time IMU feedback during operation, reducing system complexity and improving the portability properties that are critical for practical rehabilitation devices. Future work will focus on multi-user validation and investigation of user adaptation strategies. The results show that combining TSA actuation with data-driven control is an effective strategy for lightweight, sensor-independent rehabilitation exoskeletons.

## References

1. Díaz, M.A., et al.: Human-in-the-loop optimization of wearable robotic devices to improve human–robot interaction: a systematic review. IEEE Trans. Cybernet. **53**(12), 7483–7496 (2023)
2. Thalman, C., Artemiadis, P.: A review of soft wearable robots that provide active assistance: trends, common actuation methods, fabrication, and applications. Wearable Technol. **1**, e3 (2020)
3. Supriyono, C.S.A., Dragusanu, M., Malvezzi, M.: A comprehensive review of elbow exoskeletons: classification by structure, actuation, and sensing technologies. Sensors **25**(14) (2025)
4. Vélez-Guerrero, M.A., Callejas-Cuervo, M., Mazzoleni, S.: Artificial intelligence-based wearable robotic exoskeletons for upper limb rehabilitation: a review. Sensors **21**(6) (2021). https://www.mdpi.com/1424-8220/21/6/2146
5. Malvezzi, M., Suthar, B., Dragusanu, M.: Twisted string actuators: comprehensive review on modeling, design innovations, application advances, and future challenges. Measurement **257**, 118824 (2026)
6. Dragusanu, M., Guinet, N., Suthar, B., Baldi, T.L., Prattichizzo, D., Malvezzi, M.: A 3 degrees-of-freedom lightweight flexible twisted string actuators (TSAS)-based exoskeleton for wrist rehabilitation. IEEE Robot. Autom. Lett. **10**(6), 6520–6527 (2025)
7. Wang, J., Zhang, W., Guo, T., Zhou, Y.: Smart flexible wrist exoskeleton with twisted string actuators and IMU feedback. In: 2024 7th International Conference on Robotics, Control and Automation Engineering (RCAE), pp. 22–26 (2024)
8. Dragusanu, M., Troisi, D., Suthar, B., Prattichizzo, D., Malvezzi, M.: Development of a soft actuated glove based on twisted string actuators for hand rehabilitation. In: 2024 10th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), pp. 1702–1708 (2024)
9. An, J., et al.: Fabric integrated wearable glove with a twisted string actuator for manual handling tasks. Sci. Rep. **15**(1), 13185 (2025)
10. Lee, D., Lee, S., Lee, D., Shin, D.: A soft wearable robot with an adjustable twisted string actuator and a two-stage transmission mechanism for manual handling tasks. Adv. Intell. Syst. **7**(6), 2400700 (2025)

11. Dragusanu, M., Troisi, D., Suthar, B., Hussain, I., Prattichizzo, D., Malvezzi, M.: MGlove-TS: a modular soft glove based on twisted string actuators and flexible structures. Mechatronics **98**, 103141 (2024)
12. Nguyen, H., Eang, C., Lee, S.: Predicting the lifespan of twisted string actuators using empirical and hybrid machine learning approaches. Sensors **25**(23) (2025)
13. Dragusanu, M., Iqbal, M.Z., Baldi, T.L., Prattichizzo, D., Malvezzi, M.: Design, development, and control of a hand/wrist exoskeleton for rehabilitation and training. IEEE Trans. Rob. **38**(3), 1472–1488 (2022)
14. González-Mendoza, A., Quiñones-Urióstegui, I., Salazar-Cruz, S., Perez-Sanpablo, A.I., López-Gutiérrez, R., Lozano, R.: Design and implementation of a rehabilitation upper-limb exoskeleton robot controlled by cognitive and physical interfaces. J. Bionic Eng. **19**(5), 1374–1391 (2022)