15th IFK
Proc. of the 15th International Fluid Power Conference <Symposium/Conference>
<DOI>

Integration of Pneumatic Systems in Training Devices for Combat Sports

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Abstract.

The inherent compressibility of air, characteristic of all pneumatic systems, can serve as an advantageous feature in the development of conceptual solutions for training devices aimed at enhancing motor reactions required in combat sports. These devices typically consist of a supporting structure and movable components equipped with striking surfaces. Combat sports such as boxing and taekwondo have historical roots extending far into the past. Although their roles and cultural significance have evolved over time, these disciplines have gained substantial popularity in recent decades, largely due to their commercial appeal and adaptation into various forms of competitive entertainment for broad audiences. Enhancing specific muscle movements, manifested through attributes such as speed, agility, strength, precision, and endurance, is essential in combat sports and can be facilitated through specialized training devices. Pneumatic systems offer a highly efficient and adaptable platform for developing such devices, owing to their operational speed, reliability, and programmability in motion control. Their simple mechanical design and rapid actuation capabilities make them particularly suitable for sports training scenarios, where high dynamic performance and user safety are critical. Accordingly, the development of a system designed to reduce athletes' reaction times to visual stimuli would be of significant benefit. To achieve this, the pneumatic system must be equipped with appropriately selected actuators, a stable load-bearing structure, and a component arrangement tailored to match the user's physical stature. The training apparatus should also feature adjustable components, enabling vertical repositioning to align with the athlete's height, and allow programming adjustments to modulate the speed and pattern of movements, thereby providing a high degree of application flexibility. This paper presents the conceptual design and practical implementation of two devices developed for training defensive techniques and improving reaction times in martial arts disciplines such as boxing and taekwondo. The movement of the pneumatic actuators is randomized, requiring the practitioner to react quickly and appropriately, either by striking the target surface, as in taekwondo, or by dodging or blocking simulated punches, as in boxing. The system includes pneumatic valves and a control unit capable of generating random activation sequences for the pneumatic cylinders, thereby simulating unpredictable movements typical of combat scenarios. A programmable control algorithm was implemented using a Controllino device, and the

developed control software was tested on the fabricated training equipment within sports hall environments.

Keywords. Pneumatic systems, combat sports, reaction time training, martial arts equipment, programmable control.

1. INTRODUCTION

Combat sports, including boxing and taekwondo, require exceptional neuromuscular coordination, speed, precision, and agility. In recent decades, the rising popularity of these disciplines, both as professional sports and recreational activities, has driven the development of advanced training methodologies [1], [2]. A key factor in improving athletic performance in these sports is the enhancement of reaction time, particularly in response to unpredictable stimuli that closely mimic real combat scenarios [3]. Modern training equipment increasingly incorporates technologies such as electromechanical actuators, robotic systems, and sensor-based feedback mechanisms [4]. However, despite their proven effectiveness in industrial automation for tasks demanding speed, precision, and repeatability, pneumatic systems remain underutilized in sports training applications [5]. Pneumatic actuators offer several distinct advantages for athletic training devices: rapid response, smooth motion control, natural impact absorption due to air compressibility, and seamless integration with programmable control systems [6]. This study introduces a novel approach by implementing pneumatic actuation to simulate dynamic and unpredictable combat situations in a safe and controlled environment. Unlike conventional training tools, the proposed devices feature randomized movement patterns of striking or blocking elements, effectively replicating the variability of real-life sparring. Through adjustable air pressure and actuation speed, the system can be customized to suit different user profiles, enabling both novice and elite athletes to train at appropriate intensity levels [7]. Furthermore, the integration of sensors and programmable controllers (e.g., Controllino PLC) allows for real-time monitoring of reaction time, movement precision, and timing accuracy. This feedback not only enhances training effectiveness but also provides objective metrics for tracking athletic progress [8].

This paper presents the conceptual design, development, and practical implementation of two pneumatic-based training devices tailored for martial arts disciplines. The systems were tested in sports hall environments to assess usability and performance. The overarching goal is to contribute to the advancement of intelligent and adaptable sports training equipment that improves reflexive responses and overall athletic readiness in combat sports.

2. PNEUMATIC SYSTEM FOR TRAINING REACTION SPEED IN TAEKWONDO

Martial arts originated as systems of unarmed self-defence and have evolved over centuries into complex disciplines encompassing both physical and philosophical dimensions. Among these, taekwondo stands out as one of the most dynamic and globally popular sports, particularly following its inclusion in the Olympic Games in 2000. The sport emphasizes speed, agility, and precision (especially in foot techniques) and demands rapid responses to visual stimuli during combat. Traditional methods for improving reaction speed often rely on partner-based drills, where one participant initiates a movement and the other responds. While effective, these exercises require constant human interaction, limiting opportunities for individual training. To address this challenge, a pneumatic training system was developed to provide visual signals that trigger athlete reactions. This chapter outlines the design, implementation, and testing of an experimental system aimed at enhancing reaction speed in taekwondo practitioners.

2.1. System Architecture and Mechanical Design

The proposed system consists of two independently controlled double-acting pneumatic cylinders, each equipped with a circular impact target suitable for kicks or punches. Cylinder movement is regulated by 5/3 solenoid valves, controlled via a Geekcreit UNO R3 microcontroller. All components are mounted on a steel frame that ensures mechanical stability and allows for height adjustments.

The frame is constructed from 25 × 25 mm steel square tubing with a 2 mm wall thickness. Its H-shaped base, formed from four 900 mm tubes, provides a stable foundation. Vertical supports (1900 mm in height) feature machined grooves for adjusting the cylinder mounting height to accommodate different training levels.

Both pneumatic actuators are SMC CP96 cylinders with a 100 mm stroke and a 16 mm piston rod diameter. These cylinders are selected for their high actuation speed (less than 0.5 seconds) and mechanical robustness, critical for withstanding repeated impacts without deformation. Each piston rod is fitted with a 200 mm diameter, 15 mm thick circular board made of laminated wood, topped with a soft impact layer sourced from modified taekwondo armor and focus pads (Figure 2.1). To enhance safety and simulate realistic contact, the piston is depressurized after extension, reducing resistance upon impact.

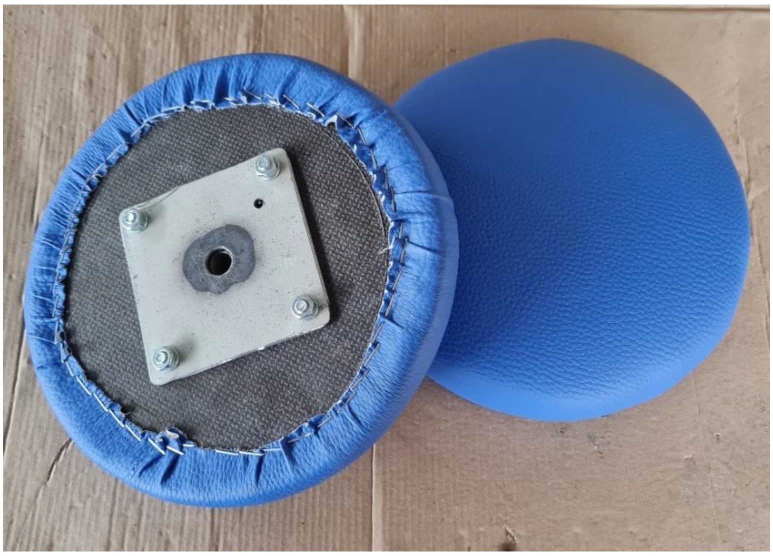


Figure 2.1. Striking Surfaces Mounted on Piston Rods for Taekwondo Training

2.2. Electronic Control System and Software

The control system is based on a Geekcreit UNO R3 microcontroller (ATmega328P), programmed via the Arduino IDE. It manages two SMC SY5000 5/3 solenoid valves that control airflow to the pneumatic cylinders.

Power is supplied by a Schrack LP 746201 AC/DC converter, delivering 24 V DC at 1.5 A, which is sufficient for valve operation and LED indicators. The microcontroller outputs are interfaced through transistors on a custom development board, ensuring safe and efficient switching of the solenoids (Figure 2.2).

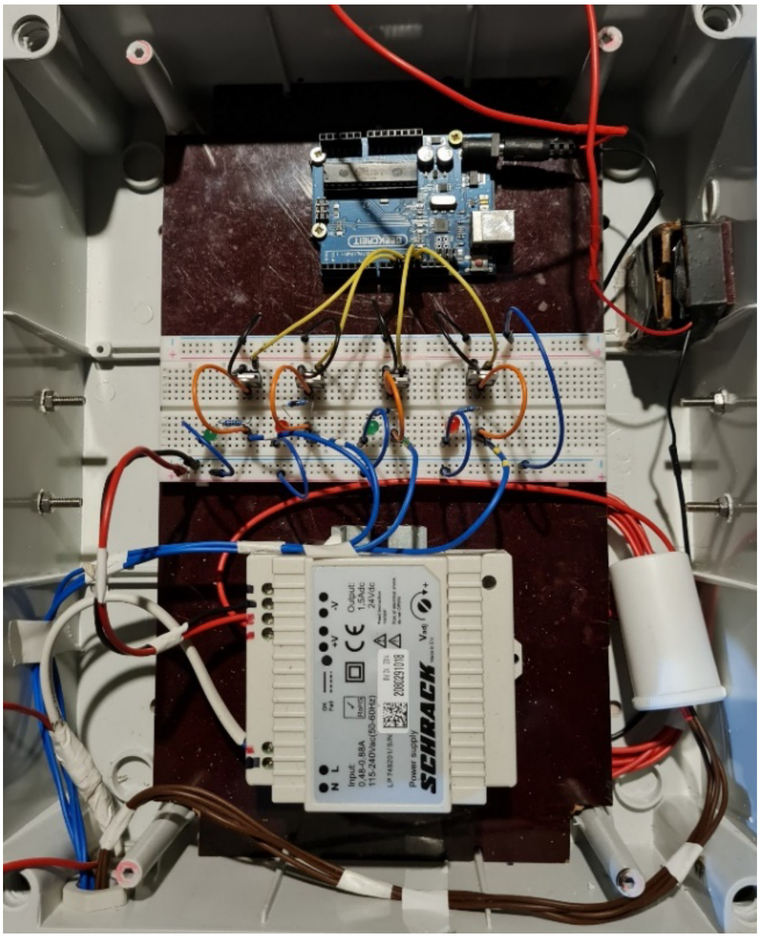


Figure 2.2. Control Box: Microcontroller, Power Supply Unit, and Interface Board

The software initializes all input/output pins and runs a continuous loop that triggers randomized delays and piston activations. This unpredictability simulates real combat scenarios and trains athletes to react quickly and make decisions under pressure. The system supports multiple training modes, including sequential activation, dual-piston challenges, and time-based drills.

2.3. *System Assembly and Field Testing*

Following component-level validation, the complete system was assembled and tested in its final configuration (Figure 2.3). Initial tests were conducted without user interaction to verify sequence logic and ensure reliable autonomous operation over ten repetitions. Subsequent tests involved athletes responding to piston activations.

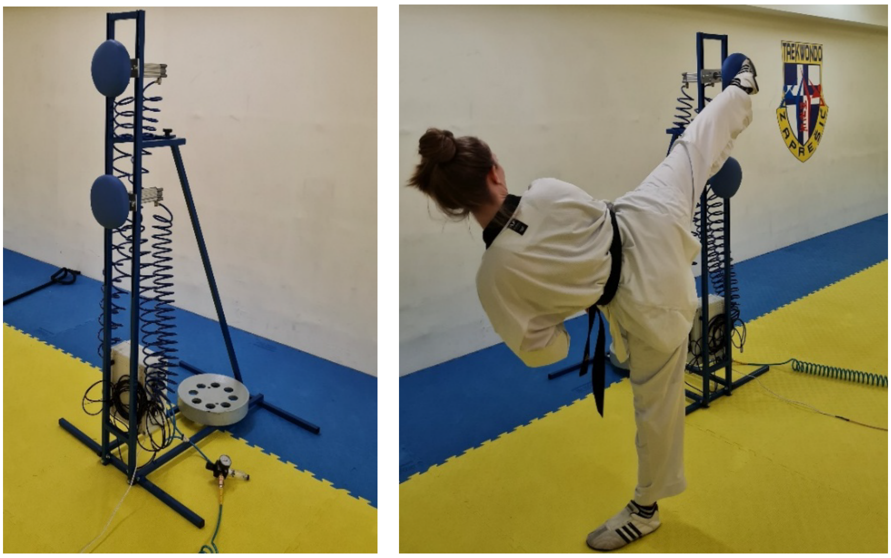


Figure 2.3. Final Design of the Taekwondo Reaction Speed Training Device in Operational Setting [9]

After minor adjustments (primarily to the height of the impact targets) the system was deployed in a school gymnasium with primary school students. The device generated strong interest and engagement, indicating high potential for youth training. Further evaluation was conducted at Taekwondo Club Zaprešić, where junior and senior athletes, including European Championship participants, used the system during regular training sessions. Various techniques were practiced, including roundhouse kicks, sidekicks, and punches at different target heights (body and head level). Reaction time was manually recorded using a stopwatch, providing a qualitative baseline for future improvements and confirming the system's effectiveness in enhancing performance. The system achieved a level of stability and safety suitable for regular integration into taekwondo training. Users expressed satisfaction with the innovative experience, especially the chance to train with unpredictable visual cues. The programmable architecture also enables future upgrades, such as:

- Integration of impact-sensitive plates for reaction time measurement;
- Monitor display for real-time feedback and performance tracking;
- Accuracy sensors for hit precision analysis.

These enhancements would transform the device from a basic reaction trainer into a comprehensive smart training platform, offering data-driven insights for athletes and coaches.

3. PNEUMATIC DEVICE FOR TRAINING DEFENSIVE TECHNIQUES AND REACTION SPEED IN BOXING

This chapter presents the development and implementation of a training device designed to improve defensive techniques and reaction speed in boxing. The system uses pneumatic cylinders to replicate incoming punches, prompting athletes to respond quickly and accurately. To ensure reliable operation, the device integrates sensors and programmed control logic that monitor each cylinder's movement, ensuring it returns to its initial position before triggering the next simulated strike. The following sections describe the mechanical design, pneumatic integration, control system, and operational behaviour of the device.

3.1. Mechanical Design and Pneumatic System Integration

The foundation of the training device is a 3D model that incorporates all mechanical and pneumatic components (Figure 3.1). The frame is built using aluminium profiles connected with angular brackets, providing a lightweight yet stable structure. Pneumatic cylinders are mounted on custom-designed plates, which are securely attached to the frame.

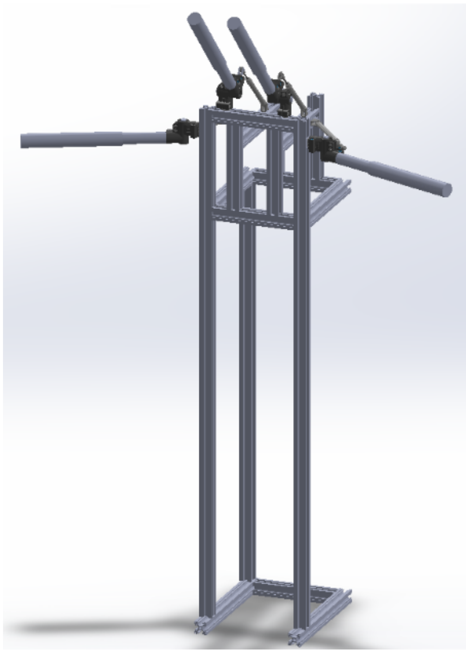


Figure 3.1. Designed 3D Model of the Training Device

The primary function of the pneumatic system is to move a focus pad from its resting position to a strike position, simulating a punch. This is achieved using double-acting pneumatic cylinders. Through CAD simulations, optimal stroke lengths were determined. The selected actuators are SMC model C(D)85N16-140C-B. System feasibility was evaluated using SMC's Model Selection Software, which simulated actuator behaviour and confirmed that the chosen cylinders meet the required performance criteria (Figure 3.2). Actuation speed is adjustable via throttle-check valves.

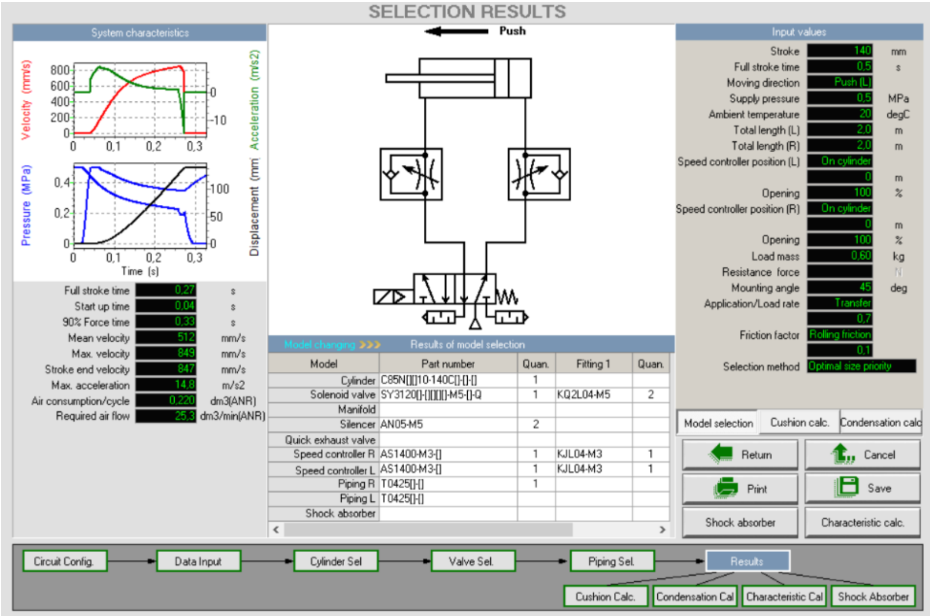
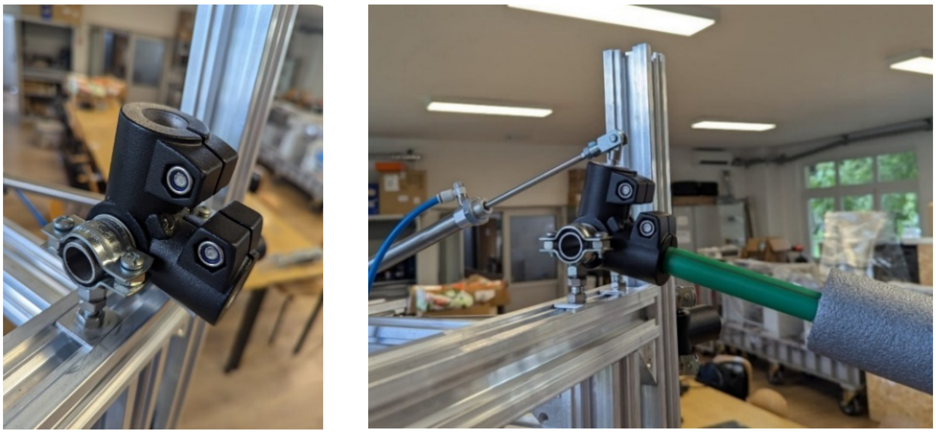


Figure 3.2. Simulation Outputs of Pneumatic Cylinder



(a) (b)

Figure 3.3. Mounting Components onto the Device Frame, a) Joint Connection to the Frame, b) Connection Between Pneumatic Cylinder and Focus Pad

The device uses four pneumatic cylinders, each paired with an angular connector to move a focus pad. These connectors are mounted on axles and rotate using sliding bearings (Figure 3.3a). The core of each pad is made from PPR pipes, chosen for their strength, affordability, and ease of customization. For safety and impact absorption, thermal insulation foam is used as the outer layer, tightly fitted without cutting. Each pad is attached via a 20 mm diameter joint connection, secured with screws (Figure 3.3b).

3.2. Control System and Electronics Integration

The pneumatic actuators are controlled by a Controllino MINI microcontroller, based on the ATMega328 platform and compatible with Arduino. Power is supplied by a 24V Mean Well MDR-20-24 unit, which drives the solenoid valves responsible for airflow control. Controllino MINI simplifies the hardware setup by integrating relay outputs used to control four SMC SY3120-5LOU-C6-Q solenoid 5/2 valves. These valves are compactly arranged on an SS5Y3-20-04-004-Q manifold. Air pressure is provided by a compressor capable of delivering up to 8 bar, connected to the pneumatic circuit via hoses and fittings. Each cylinder's speed and return flow are fine-tuned using AS1201F-M5-06A throttle-check valves with push-lock adjustment. Position sensors (D-M9PL) are powered by Controllino's 5V supply and provide real-time feedback on cylinder status, ensuring safe and accurate operation. All electronic components are housed within a protective control box, as depicted in Figure 3.4.

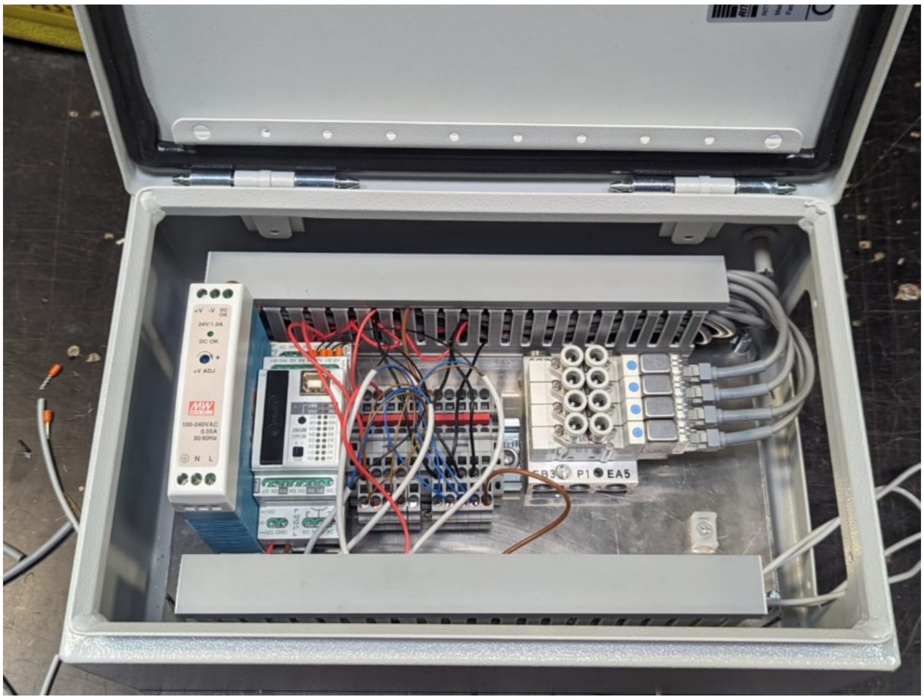


Figure 3.4. Control Unit with Integrated Components

3.3. Operating Principle and System Behavior

The device operates by randomly activating pneumatic cylinders to simulate unpredictable strikes. The control logic ensures that only one cylinder is active at a time and that each activation occurs only after the previous cylinder has returned to its resting position. System initialization involves setting air pressure and adjusting throttle valves to control actuation speed. Training parameters such as strike frequency and response intervals are configured via the Arduino interface.

During operation, the microcontroller continuously monitors sensor inputs. When a randomly selected cylinder is confirmed to be idle, a control signal activates the corresponding valve, initiating the strike. After a brief dwell time to simulate impact, the valve is deactivated, allowing the cylinder to return via spring force or reverse pressure. This cycle repeats, creating a dynamic and reactive training environment.
To ensure safety, the system halts if a sensor fails to confirm a cylinder's position, preventing unintended activation. The fully assembled device is shown in Figure 3.5, illustrating both idle and active states.

(a) (b)

Figure 3.5. Completed Training Device, a) Idle State, b) During Simulated Strike

This device successfully integrates mechatronic and pneumatic technologies to deliver a responsive, safe, and realistic training platform for boxing. Its modular design and programmable features provide a solid foundation for future enhancements, including adaptive difficulty levels, advanced strike pattern algorithms, and real-time performance analytics.

4. CONCLUSION

This study has demonstrated the practical feasibility and benefits of integrating pneumatic systems into training devices for combat sports, specifically taekwondo and boxing. By harnessing the core advantages of pneumatic actuation, such as rapid response, impact absorption through air compressibility, and seamless integration with programmable control systems, two distinct training prototypes were successfully designed, built, and tested in real-world sports environments. The taekwondo-focused device aimed to improve reaction time by presenting randomized visual targets through the extension of striking surfaces.

Athletes were challenged to respond with speed and precision to unpredictable stimuli. Field testing with both youth and professional practitioners revealed strong engagement and confirmed the system's effectiveness in enhancing reflexes and decision-making under pressure. The boxing training device simulated incoming punches using four independently controlled pneumatic cylinders. Athletes practiced defensive manoeuvres such as dodging and blocking, guided by randomized actuation sequences managed by a Controllino microcontroller. Sensor feedback and mechanical safeguards ensured safe operation, while the modular design allowed for personalized adjustments based on user height and skill level. Both devices proved to be stable, adaptable, and safe for use in various training scenarios. They offer a new paradigm in combat sports training, where mechanical systems are used not only to mimic combat situations but also to enhance athletic performance through precise control, repeatability, and data-driven feedback mechanisms.

Future improvements may include the integration of sensor-based performance tracking (e.g., impact sensors, motion detection), real-time feedback through visual or auditory interfaces, and machine learning algorithms for adaptive training programs. Such upgrades would elevate these devices from experimental prototypes to intelligent training platforms, aligned with the broader digital transformation in sports science and athlete development. In summary, the integration of pneumatic systems into combat sports equipment presents a promising and underexplored avenue for improving reaction speed, technical proficiency, and training efficiency. This work contributes to the growing intersection of mechatronics and sport, opening new possibilities for innovation in athletic training technologies.

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Biographies

Željko Šitum received his M.Sc. degree in Mechanical Engineering from the University of Zagreb, Croatia, in 1997, and his Ph.D. degree in the same field in 2001. He is currently a Full Professor at the Department of Control Engineering, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. His research interests include digital control of dynamic systems, fluid power systems control, mechatronics, and computer simulations. His current focus is primarily on modelling and control of hydraulically and pneumatically actuated robotic systems.

Tin Stanišak graduated in 2021 from the Automation in Production study program at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia. He currently works as a Metrology Coordinator at the pharmaceutical company Pfizer Croatia. He is a professional leader with extensive experience and serves as the head coach of the Plamen Pušća Taekwondo Club.

Dominik Šarić is a fifth-year student in the Mechatronics and Robotics program at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia. During his high school years, he was an active boxing competitor, achieving notable success, including the title of vice-champion of Croatia. In addition to his academic commitments, he currently works as a boxing coach and has trained numerous national champions across various boxing categories.