A Robust Open-source Tendon-driven Robot Arm for Learning Control of Dynamic Motions

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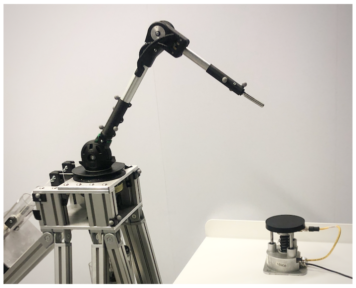
1 Introduction

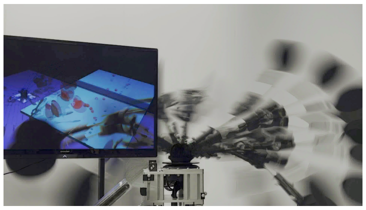
Human athletic movements, such as those seen in table tennis or soccer, require a dynamic interplay of power, agility, and precision. They also involve quick reactions to unpredictable stimuli, while effectively managing impacts and maintaining safety during rapid interactions. Such complexities pose challenges for robots aiming to emulate or collaborate with humans in sports settings. Most commercial robots are either precise yet fragile or safe yet underpowered. Tendon-driven robots provide a middle ground, lessening impact risks due to low inertia. Still, they often face precision issues due to unpredictable friction.

Our paper presents a newly designed 4-DoF tendon-driven robot arm, powered by pneumatic artificial muscles (PAMs), designed to minimize friction. This design achieves high force, low inertia, backdrivability, and superior precision compared to counterparts. While PAMs add complexities in control due to their nonlinear nature, reinforcement learning (RL) proves effective in handling them [1]. Our robot's design also mitigates RL's collision risks during explorative training.

To foster further innovations, both the robot's hardware and software are made open-source. The hardware predominantly employs readily available parts. Our software offers an adaptable API in Python and C++ based on the o80 framework [2], interfacing with the robot's PLC over UDP. We will also open-source a huge proprioceptive data-set (25 days) including motion data at various speeds and forms.



(a) Collision force measurements



(b) Table tennis smashing motion

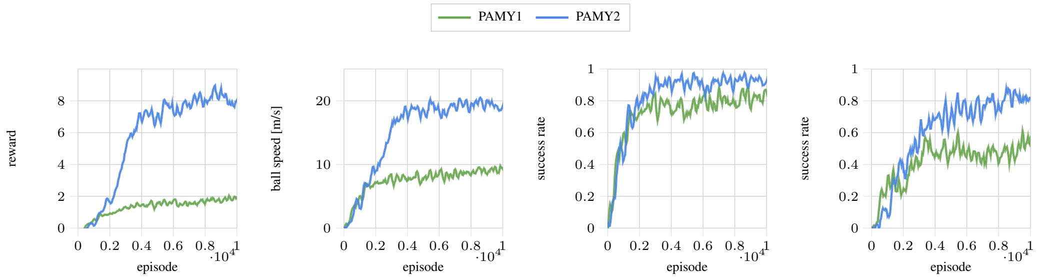
Figure 1: Experiments performed to validate PAMY2. (a) Experimental setup for the collision force measurements. A Pilz PRMS is mounted to a table onto which the end effector of the robot is colliding. (b) Table tennis smashing experiment.

2 PAMY2: Design & Implications

We introduce PAMY2, a newly designed version of the tendon-driven robot PAMY1 from Büchler et al. [3, 4]. Whereas the arm of PAMY1 was a purchased component, our design for PAMY2 is an in-house creation, featuring enhancements in mechanical design, Bowden tubes, bearings, and pneumatics. These improvements target increased impact safety, durability, and control ease. Our emphasis on safety led to a tendon-driven design with passively compliant actuators situated at the robot's base. This reduces moving masses (appr. $1.3\,\mathrm{kg}$) and inertia. The use of PAM actuators ensures passive compliance, naturally cushioning against external forces, eliminating the need for intricate control strategies in collision avoidance.

For optimized control and durability, we utilize Polytetrafluoroethylene (PTFE) for our Bowden tubes, reducing friction and heat, while enhancing the tendon's lifespan. This design, complemented by an inner tube and custom 3D-printed outer supports, ensures a consistent tendon length during

Submitted to the 7th Conference on Robot Learning (CoRL 2023). Do not distribute.



(a) Reward (b) Returned ball speed (c) Racket hits ball (d) Ball lands within target circle (R=68.5 cm)

Figure 2: Table tennis smashing experiment from [1] with identical setting (incl. hyperparameters) but with PAMY2 instead of PAMY1 [3, 4]. (a) PAMY2 reaches 4× of the final performance of PAMY1. (b) The velocity of the returned ball is appr. twice as high. (c) Although harder to control precisely, the agent misses the ball less often and (d) returns it more likely to the desired ball landing region.

movements, thereby improving precision. We've replaced previous gliding bearings with ball bearings to further decrease friction. Our updated pneumatics offers better airflow through enhanced tube routing, a buffer reservoir for stable air pressure, and a ring circuit for consistent pressure distribution.

3 Experiments & Evaluations

We assessed our new robot arm's capabilities in terms of impact safety, robustness, ease of control, and precision during fast movements.

Impact Safety: Our tendon-driven arm promises enhanced safety over traditional motor-driven systems due to its lightweight design achieved by placing the heavy actuators at the base. Using the Pilz Robot Measurement System (PRMS) to gauge collision forces (Figure 1a), our arm showed superior safety, achieving similar force levels as conventional systems but at nearly quadruple the speed (see Figure 3).

Robustness: For reinforcement learning to be effective, the robot's longevity is paramount. We tackled friction, a known wear-and-tear contributor in tendon-driven robots. Our study revealed that the redesigned Bowden tubes produce less heat, signifying reduced friction compared to the system in [3]. We also released a dataset of a 25-day continuous operation, confirming our robot's durability and consistency during dynamic tasks.

Ease of Control: Improving linearity of a system makes control easier. Comparing our new system, PAMY2, with its predecessor, PAMY1, the former exhibited better amplitude responses and significantly reduced nonlinearity during dynamic actions. Furthermore, replicating a table tennis smashing experiment from [1] (Figure 1b), using Proximal Policy Optimization (PPO) [6] for learning, we achieve significantly higher ball speeds while improving on precision, demonstrating the benefits of the new design for highly dynamic and precise motions (Figure 2).

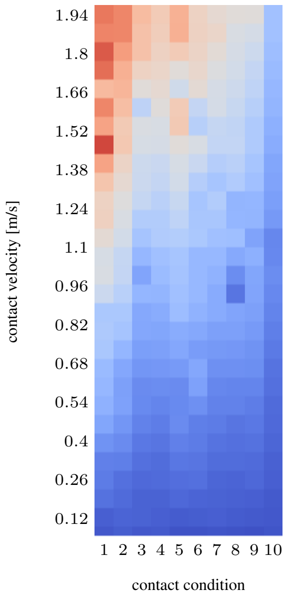


Figure 3: Force map for PAMY2, showing peak impact forces across impact velocities and contact situations [5].

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