QDD-MM: A Simple and Compact Open-Source Muscle Module with Quasi-Direct-Drive Motor for Tendon-driven Robots

Kento Kawaharazuka[1], Yoshimoto Ribayashi[1], Takahiro Hattori[1], Shunnosuke Yoshimura[1], and Kei Okada[1]

***Abstract*— Tendon-driven robots, which actuate like biological muscles by using motors to wind wires, offer advantages such as variable stiffness and redundant actuation. Despite these advantages, musculoskeletal structures inherently involve a large number of diverse muscles, making it desirable to compactly modularize each muscle unit and flexibly accommodate diverse muscle arrangements. While various small muscle modules have been proposed to date, existing designs tend to be complex, difficult to maintain, and suffer from low backdrivability and limited actuation speed due to their high gear ratios. In this work, we propose QDD-MM, a muscle module that leverages recent advances in quasi-direct-drive motors to achieve a simpler and more compact structure with higher backdrivability and faster actuation than previous modules. By utilizing quasi-direct-drive motors, the module eliminates the need for dedicated force-sensing mechanisms, significantly simplifying the overall design, while also supporting flexible wire routing in multiple directions, various module-to-module connections, and even the use of the module body itself as a structural component. QDD-MM integrates these capabilities into a reusable muscle module, and its design is openly available at github.com/haraduka/qddmm. We developed tendon-driven robots with one joint and either two or three muscles, as well as a partial musculoskeletal humanoid, using the proposed QDD-MM and verified their effectiveness. We expect that this muscle module will democratize tendon-driven robotics and further accelerate progress in the field.**

I. INTRODUCTION

A variety of tendon-driven humanoids that closely mimic human anatomical structures have been developed to date [1]–[4]. Beyond purely biological imitation, many tendon-driven robots have been created to leverage the advantages of wire-driven actuation [5]–[9]. These robots offer numerous benefits, such as enabling variable stiffness control through nonlinear elastic elements [10], [11], maintaining functional operation even after muscle failure due to redundancy [12], allowing flexible changes in body morphology by reconfiguring wire routing [9], and reducing the weight of distal body segments by proximally locating actuators [7], [8].

However, musculoskeletal structures tend to become complex because they involve a large number of diverse muscles. Thus, it becomes crucial to compactly modularize each muscle and to ensure that the muscle module can accommodate a wide variety of possible muscle arrangements. If the same muscle module can be used across different body parts, the design and fabrication of tendon-driven robots become significantly easier, and maintainability is improved.

[1] The authors are with the Department of Mechano-Informatics, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. [kawaharazuka, ribayashi, t-hattori, yoshimura, k-okada]@jsk.imi.i.u-tokyo.ac.jp

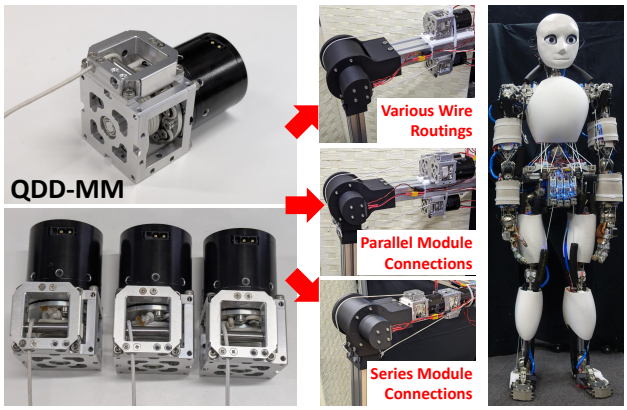


Fig. 1. The concept of QDD-MM: a compact muscle module (left) and configurable tendon-driven mechanisms (middle). The full humanoid (right) illustrates the intended application.

Motivated by these challenges, several small muscle modules have been proposed in previous work [2], [13]–[15]. These modules commonly have adopted a slender cylindrical form factor and integrate a BLDC motor, a custom motor driver, a pulley for wire winding, and a tension sensor. Although relatively compact and capable of supporting diverse wiring configurations, these modules employ small motors paired with high gear-ratio transmissions for miniaturization. As a result, they suffer from low backdrivability and limited actuation speed. Furthermore, the high gear ratio makes it difficult to estimate muscle tension from motor current alone, necessitating dedicated force sensors. This increases structural complexity and reduces maintainability. QDD actuation has also been applied to cable-driven robots. Mi et al. developed a modular tensegrity robot with QDD cable actuators, enabling force estimation and variable stiffness control without external force sensors [16]. Sawaguchi et al. developed Vlimb, a wire-driven wearable robot using AK60-6 actuators and reconfigurable wire routing to balance lifting capability and reachability [17]. These studies establish the applicability of QDD actuation to cable-driven systems. Our focus is an open-source, reusable muscle module with configurable wire outlets and module connections, together with a direct experimental comparison against a conventional high-gear-ratio muscle module.

In this work, we propose Quasi-Direct-Drive Muscle Module (QDD-MM), a muscle module that leverages quasi-direct-drive motors [18] to achieve a simpler and more compact design, while providing high backdrivability and fast actuation that exceed those of previous muscle modules. Recent advances in quasi-direct-drive motors have significantly improved torque density and efficiency, making

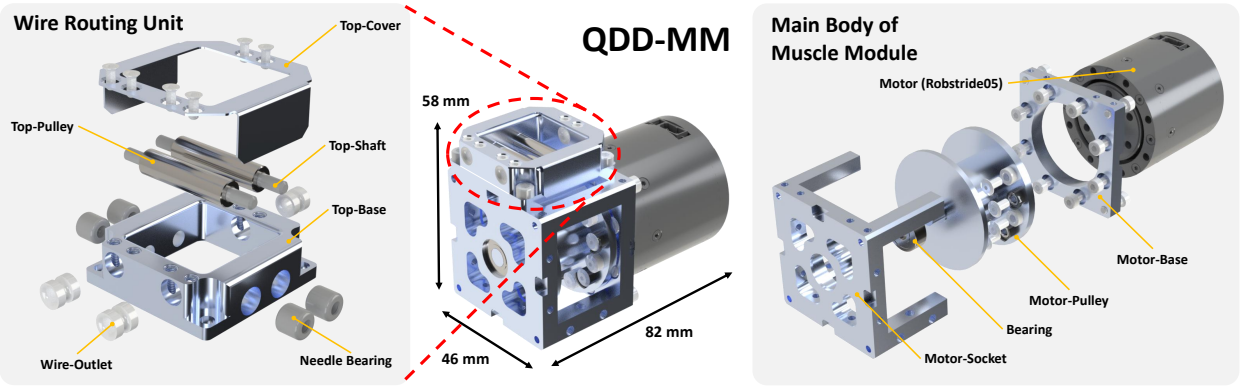


Fig. 2. Design overview of QDD-MM: the muscle module consists of a main body integrating a quasi-direct-drive motor and pulley system, and a detachable wire routing unit that defines the wire's pulling direction.

it possible to generate sufficient muscle force even with low gear ratios. Consequently, by reducing the gear ratio, backdrivability can be improved and dedicated force-sensing mechanisms can be removed, which greatly simplifies the structure of the muscle module. In addition, QDD-MM retains the capabilities of previous modules, such as flexible wire routing in multiple directions and support for various module-to-module connections. It also introduces a mechanism that allows the module itself to serve as a structural component of the robot body. The contribution of QDD-MM lies in integrating configurable wire routing, parallel and series module connections, and structural use of the module body into a compact, open-source design available through the Supplementary Materials. The high torque density and backdrivability originate primarily from the commercial QDD actuator; our module design makes these properties usable across different tendon-driven structures through common mechanical interfaces. Fig. 1 illustrates the concept of constructing diverse tendon-driven robots from a common muscle module, with the full humanoid on the right representing a future application. Using QDD-MM, we constructed tendon-driven robots with one joint and either two or three muscles, as well as a partial musculoskeletal humanoid, and we verified their effectiveness experimentally. We show that a simple one-joint–two-muscle tendon-driven robot can be extended by using an additional muscle through modular connections, and that a compact tendon-driven robot can be realized by using the muscle module itself as a skeletal structure. These results suggest that tendon-driven robots, which have long been considered difficult to work with, may become increasingly accessible and continue to advance through the use of the proposed module.

II. QDD-MM: Simple and Compact Muscle Module with Quasi-Direct-Drive Motor

A. Basic Structure of Muscle Module

The basic structure of the muscle module QDD-MM developed in this study is shown in Fig. 2, and all components of QDD-MM and its surrounding parts are shown in Fig. 3. QDD-MM has a simple and compact design and consists of two major elements: the main body, which includes a quasi-direct-drive motor and the Motor-Pulley for wire winding, and the wire routing unit. For the main body, we use a RobStride05 motor. The motor driver is integrated into the unit, allowing control via CAN communication. A pulley with a diameter of 24 mm is mounted on the motor shaft (the diameter can be changed), and the motor generates muscle tension by winding a 2 mm-diameter Zylon wire around the pulley. The motor provides a continuous torque of 1.6 Nm, and with a pulley radius of 12 mm, the maximum continuous tension is 133 N. The wire routing unit includes two Top-Pulleys that change the direction of wire extraction, but only one Top-Pulley is needed depending on the configuration. The wire can be drawn from any of the three Wire-Outlets. To withstand the applied wire tension, small needle bearings are used. QDD-MM consists of four machined metal parts and one sheet-metal part, and the module connector used to link multiple QDD-MM units (described in detail in Section II-C) consists of four machined parts. All machined components are made of A7075 aluminum alloy, and the sheet-metal components are made of A5052.

Fig. 4 shows how the wire is attached to the Motor-Pulley. The end of the wire is tied and then passed alternately through seven small pulleys, which secure the wire through friction. Based on Euler's belt theory, $f_1 = f_0 e^{\mu\theta}$, even when the friction coefficient $\mu = 0.3$ between the small pulleys and the wire, seven pulleys provide a total wrap angle of 3.5 turns ($\theta = 3.5 \times 2\pi$). As a result, the tension at the wire end f_0 becomes $1/731$ of the input tension f_1. Since the maximum input tension f_1 is 133 N, the resulting tension at the wire end f_0 is only 0.18 N, which is extremely small.

B. Various Wire Routings

QDD-MM allows wires to be routed in various directions through its wire routing unit. This capability is highly important, as it significantly increases the design flexibility of tendon-driven robots. Fig. 5 illustrates several examples of wire extraction directions. The wire routing unit can be mounted on either the left or right side, and it can be attached to the main body in four different orientations. As a result, the wire can be drawn forward, backward, leftward, or rightward. Here, only one of the Top-Pulleys is used. When two Top-Pulleys are installed, the wire can also be routed upward instead of being extracted from a Wire-Outlet.

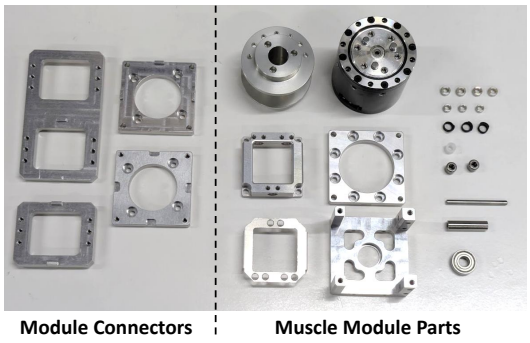


Fig. 3. All components of QDD-MM consisting of muscle module parts, which constitute the muscle module, and module connectors, which link these modules together.

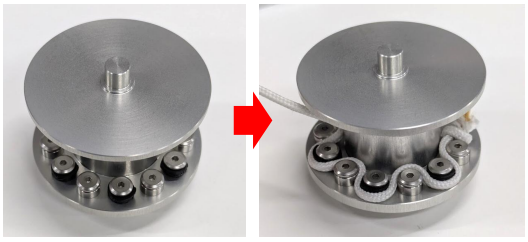


Fig. 4. Wire connection method to the Motor-Pulley: the wire end is tied, and then passed alternately through seven small pulleys in a weaving manner, allowing the wire to be secured by friction.

C. Various Module Connections

QDD-MM units can be freely connected to one another. As shown in Fig. 6, the four module connectors have interlocking convex and concave structures that allow two muscle modules to be joined securely with screws. Examples of these connections are shown in Fig. 7. By using two types of module connectors for the right, left, and downward directions, two muscle modules can be connected in parallel. For the forward and backward directions, two additional types of module connectors are used to connect modules in series. When combined with different mounting positions for the wire routing unit, this design accommodates a wide range of muscle arrangements. The forward and backward connections are particularly important, as they allow the muscle module itself to serve as part of the robot's skeletal structure, thereby enabling seamless integration of bone and muscle components in a compact form.

D. Comparison with Existing Muscle Modules

When comparing the proposed QDD-MM with previously developed muscle modules [14], [15] shown in Fig. 8, the prior modules have a slender cylindrical shape and consist of a BLDC motor, a custom motor driver, a pulley for wire winding, and a tension measurement unit. Because these motors have low torque density and cannot generate high torque on their own, they are combined with high gear-ratio transmissions. As a result, the modules exhibit low back-drivability and slow actuation speed. In addition, due to the low transmission efficiency of the gears, estimating muscle tension from motor current is difficult, which necessitates the use of a tension sensor mounted on the wire routing unit. In contrast, QDD-MM employs a quasi-direct-drive

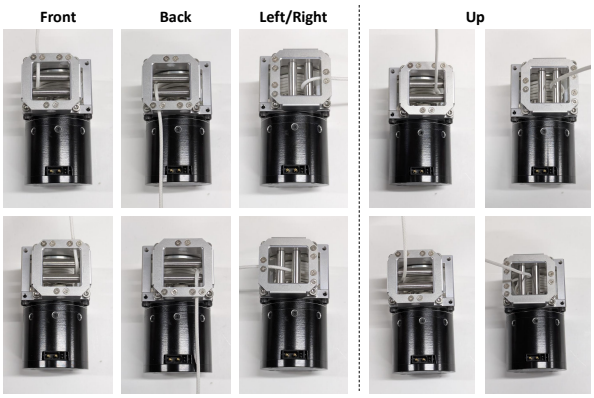


Fig. 5. Various wire routing directions: by changing the orientation of the wire routing unit, the wire can be routed forward, backward, leftward, rightward, or upward.

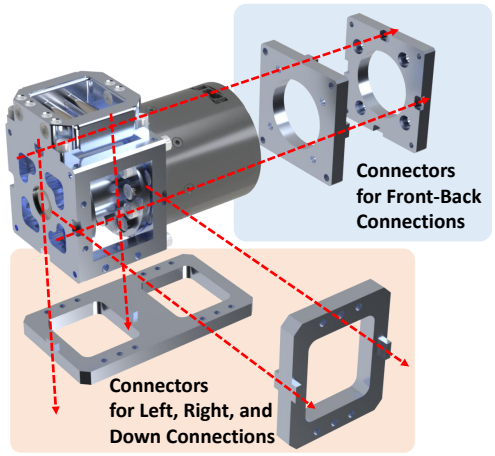


Fig. 6. The four module connectors have interlocking convex and concave structures, enabling connection between modules in five directions: forward, backward, leftward, rightward, and downward.

motor, eliminating the need for a muscle tension sensor and greatly simplifying the overall structure while achieving high backdrivability and fast actuation. The method of attaching the wire to the pulley also differs significantly. In previous muscle modules, a hole was drilled orthogonally through the pulley, and the wire was passed through and tied on the opposite side. However, this design causes the wire to bend sharply with a minimum bending radius of approximately 0.1 mm near the starting point, placing almost all the load on the knot. This greatly reduces wire durability. QDD-MM improves wire handling by routing the wire alternately through seven small pulleys, increasing the minimum bending radius to 3 mm and fixing the wire through friction instead of relying on a knot. This substantially enhances durability. The wire material has also been updated: earlier systems used 3 mm or 2 mm Dyneema, whereas QDD-MM employs 2 mm Zylon, which has a higher elastic modulus and is therefore less prone to elongation. Furthermore, the connection between the motor and the pulley has been revised. Previous modules relied on a D-cut shaft secured with a set screw because the motor shaft was thin. In QDD-MM, the motor and pulley are instead directly connected using a dowel pin, providing a more robust and reliable connection. These improvements in the wire attachment

TABLE I

COMPARISON AMONG MINIATURE BONE-MUSCLE MODULE [15], SENSOR-DRIVER INTEGRATED MUSCLE MODULE [14], AND QDD-MM.

	Miniature bone-muscle module [15]	Sensor-driver integrated muscle module [14]	QDD-MM (this study)
Module dimensions [mm^3]	$32.0 \times 40.0 \times 126$	$22.0 \times 40.5 \times 149$	$46.0 \times 58.0 \times 82$
Module weight [kgf]	0.30	0.32	0.34
Number of actuators	2	1	1
Actuator type	Maxon BLDC-60W	Maxon BLDC-120W	RobStride05
Gear ratio	84:1	53:1	7.75:1
Pulley diameter [mm]	8	12	24 (12)
Continuous maximum tension (motor) [N][*1]	260	284	133 (267)
Continuous maximum tension (gear) [N][*2]	100	133	-
No-load winding speed [mm/s]	216	200	603 (302)

[*1] Since the original papers [14], [15] did not take gear transmission efficiency into account, the reported values differ from those in the previous works.
[*2] Maximum continuous tension determined by gear strength

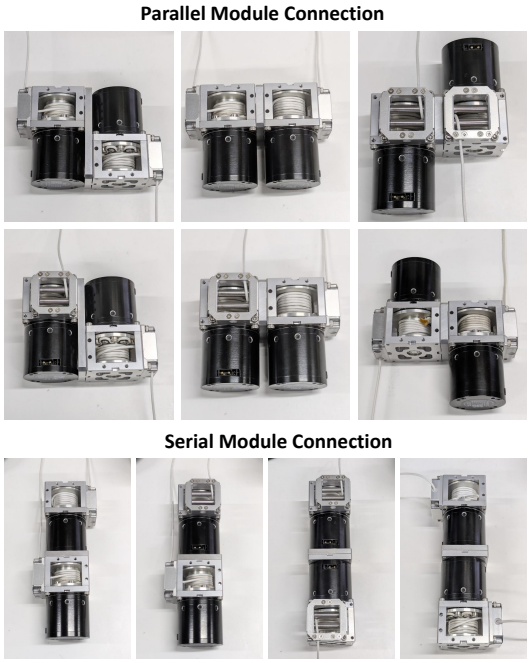


Fig. 7. Various connections between muscle modules: two muscle modules can be connected to each other to the right, left, and downward using two types of module connectors, and to the front and back using the other two types of module connectors.

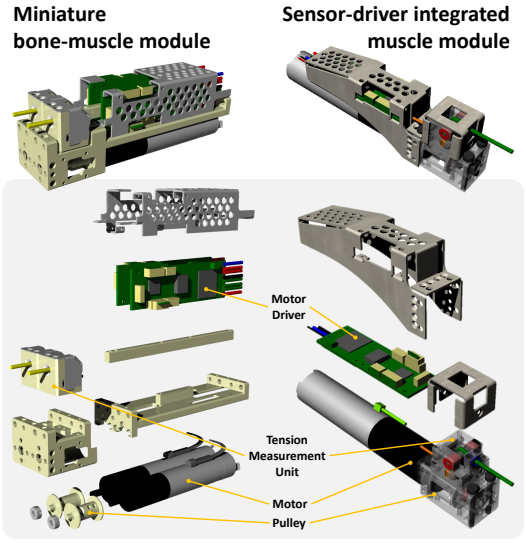


Fig. 8. Conventional muscle modules: composed of an elongated motor with a high gear ratio and pulley, a tension measurement unit, a motor driver, and their protective covers.

method to the pulleys and in the connection between the motor and the pulley became possible only after the form factor of the muscle module changed from a slender shape to a stubby one, and they represent important advancements over previous designs.

Table I presents a numerical comparison between QDD-MM and previous muscle modules. Although QDD-MM is slightly larger in width and height, its depth is significantly shorter, and its overall mass is nearly the same as that of earlier modules. In terms of gear ratio, previous muscle modules employed high ratios such as 84:1 and 53:1, whereas QDD-MM uses a markedly lower ratio of 7.75:1 with a single-stage planetary gearbox. The pulley diameter of QDD-MM can be freely adjusted. For example, when set to 12 mm, the maximum continuous tension determined by motor limitations becomes 260 N, 284 N, and 267 N for each muscle module, enabling QDD-MM to achieve tension levels comparable to previous designs. Despite this, the wire winding speed is approximately 1.5 times faster than that of existing muscle modules, and the low gear ratio results in a substantial improvement in backdrivability. In addition, previous muscle modules suffered from insufficient gear strength; in practice, the gears would fail if forces of 100 N or 133 N were applied continuously. QDD-MM avoids this issue due to its low gear ratio. Note that, in this study, we prioritize fast actuation, and therefore the pulley diameter was set to 24 mm in our implementation.

In this way, applying QDD motors to muscle modules resolves many of the longstanding challenges found in previous designs. The force and speed characteristics reflect both the selected QDD actuator and the pulley radius; they are not independent innovations of the module. Beyond the QDD cable actuation demonstrated in [16], [17], QDD-MM provides a reusable mechanical interface for changing muscle number, routing, and structural arrangement, and evaluates the resulting module against conventional muscle modules. Its open-source design complements existing open-source tendon-driven robots [19] by providing a muscle unit that can be reused across robot designs.

III. EXPERIMENTS

A. Basic Performance Experiment

We conducted experiments to evaluate the basic performance of the proposed QDD-MM and a previous muscle

module (Previous) [14]. The module in [15] was not included in the comparison, as its specifications are nearly identical to those in [14].

First, we conducted an experiment to evaluate backdrivability. The QDD-MM and the previous muscle module were mounted on a tabletop tensile testing setup, and the wire was pulled at a constant speed of 5 mm/s. Backdrivability was then evaluated from the resulting resistive force. The relationship between wire extension and resistive force was measured three times for each module, and the mean and variance were calculated. The results are shown in Fig. 9. While the previous muscle module exhibited a resistive force of approximately 8 N, the QDD-MM showed a resistive force of only about 4 N, indicating that the QDD-MM has approximately twice the backdrivability of the previous module. On the other hand, because the QDD-MM employs a quasi-direct-drive motor, it exhibits relatively large cogging torque, resulting in larger fluctuations in the resistive force.

Next, we conducted an experiment to investigate the relationship between the commanded muscle tension and the actual muscle tension. Each muscle module and a force gauge were aligned in a straight line. Current control was applied to increase the commanded tension from 0 to f^{ref} over 10 seconds, followed by a 5-second hold, and then decreased back to 0 over another 10 seconds. The value of f^{ref} was set to 50, 100, 150, and 200 N, and each condition was repeated twice. We then measured the relationship between the commanded muscle tension and the actual tension obtained from the force gauge. The conversion from commanded tension to motor current considered the pulley radius, gear ratio, and gear transmission efficiency, although losses at the Top-Pulley, Motor-Pulley, and the tension measurement unit were not included. The results are shown in Fig. 10. Both muscle modules achieved approximately 90% of the commanded tension, and we attribute the remaining 10% loss to friction within the pulleys and tension measurement unit, which were not accounted for in the conversion model. Here, hysteresis means that the measured tension at the same command depends on whether the command is increasing or decreasing. Each cycle follows an increasing branch from 0 to f^{ref}, a hold at f^{ref}, and a decreasing branch back to 0. The vertical separation between the two branches at the same command indicates the history dependence. The most significant difference between the previous muscle module and QDD-MM is found in these hysteresis characteristics. Due to the high gear ratio and low backdrivability of the previous module, substantial hysteresis occurs between the pulling and releasing phases. For example, when the command tension is reduced from 200 N to 70 N, the previous module fails to unwind and still produces about 160 N of tension. In contrast, QDD-MM produces only about 80 N under the same condition, demonstrating considerably smaller hysteresis. In other words, while it was almost impossible to estimate muscle tension from motor current in previous modules, QDD-MM exhibits an approximately proportional relationship between motor current and actual muscle tension. This supports current-based tension estimation without a dedicated tension sensor in the demonstrated applications, while residual friction and hysteresis still introduce estimation error.

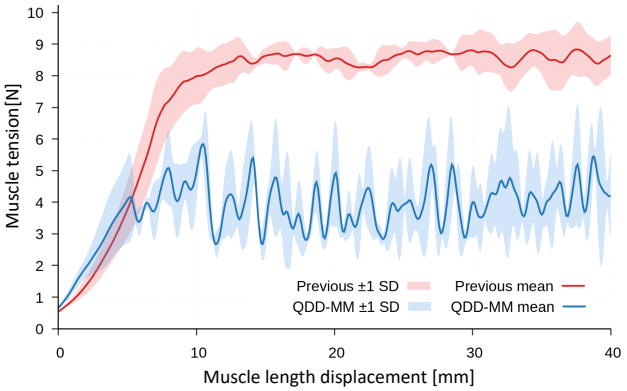


Fig. 9. The relationship between the muscle length displacement and muscle tension for the previous muscle module [14] (Previous) and QDD-MM.

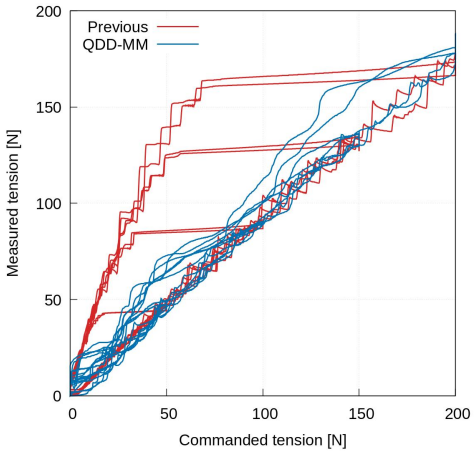


Fig. 10. The relationship between the commanded and measured muscle tensions for the previous muscle module [14] (Previous) and QDD-MM.

B. 1-DOF Tendon-driven Robot Experiment

This experiment evaluates reconfigurability, joint-angle tracking, and load sharing using one-joint robots with two or three QDD-MMs. Fig. 11 illustrates examples of the robot configurations used in the experiments. Configuration (1) is a one-joint–two-muscle tendon-driven robot, in which two QDD-MM units are attached to a bone frame using module connectors. Configuration (2) extends (1) by using an additional muscle module in parallel via a module connector, thereby creating a one-joint–three-muscle robot. Configuration (3) connects two muscle modules in series via the module connector so that the modules themselves function as the skeletal structure, resulting in a compact one-joint–two-muscle tendon-driven robot.

For each of the three robots, the commanded joint angle was moved from 0 to -90 degrees over 2 seconds, held for 1.5 seconds, and then returned over another 2 seconds. This cycle was repeated while measuring joint angles and muscle tensions. The control method was a standard muscle-tension-based approach: the joint-angle error was converted into joint torque using PD control, and the required torque was

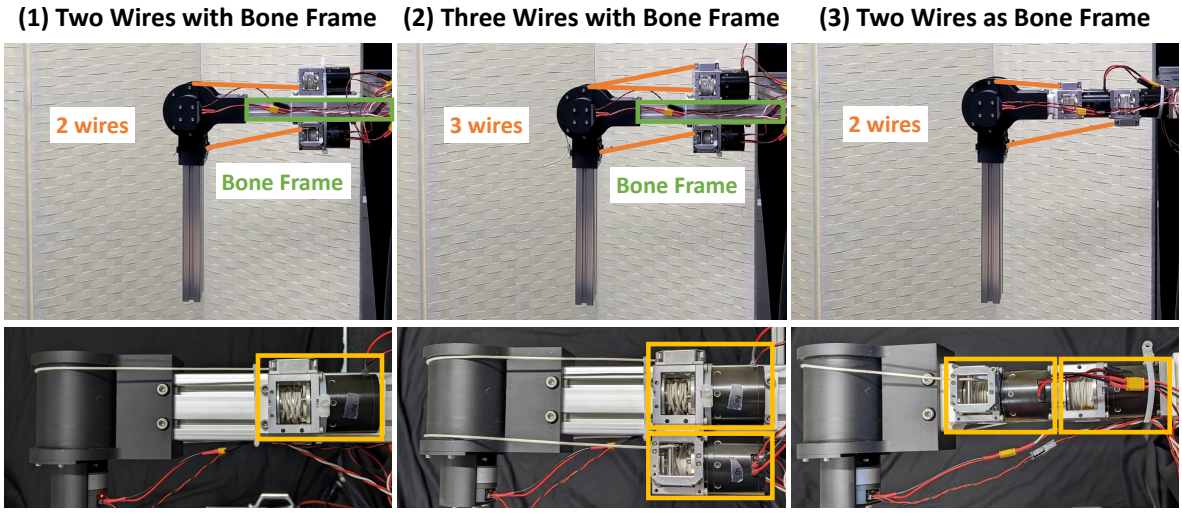


Fig. 11. Experimental setup: the left panel shows a configuration with two muscles attached to the bone frame, the middle panel shows a configuration with three muscles realized by adding a module in parallel, and the right panel shows a series connection in which the module itself is used as the bone frame.

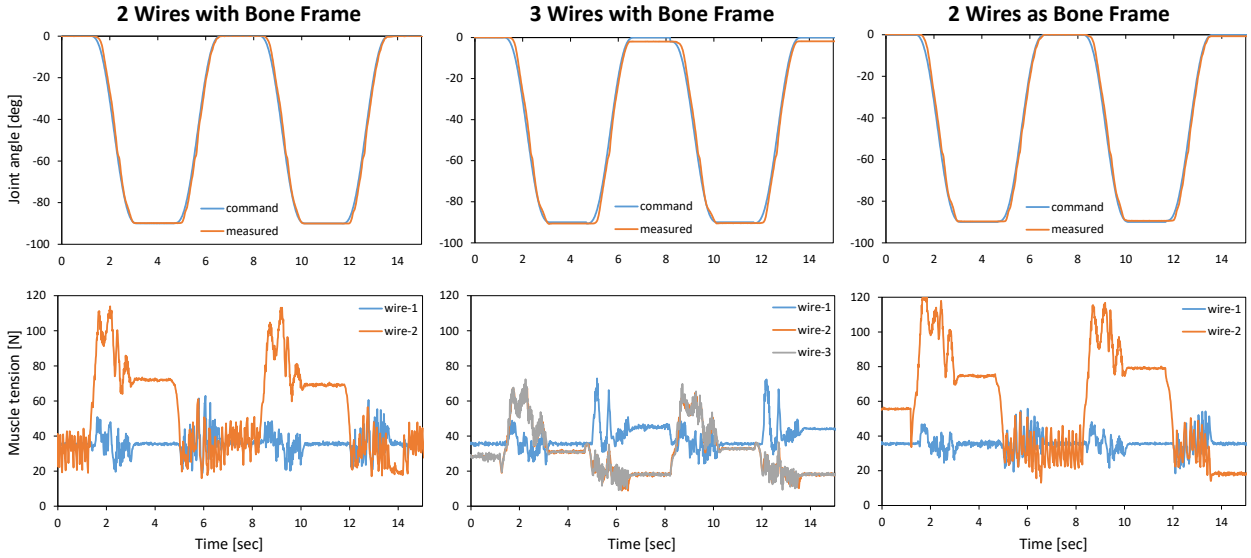


Fig. 12. The experimental results corresponding to Fig. 11, including the commanded and measured joint angles as well as the measured muscle tensions.

allocated to the muscles [20]. The minimum tension for the antagonist muscle (wire-1) was set to 30 N, and the minimum tension for the agonist muscles (wire-2 or wire-3) was set to 15 N. The results are shown in Fig. 12. All three tendon-driven robots were able to track the commanded joint angles with reasonably good accuracy. Regarding muscle tension, configurations (1) and (3), which both use two muscles, exhibited similar tension profiles. In contrast, configuration (2), which uses three muscles, demonstrated cooperative behavior between wire-2 and wire-3, reducing the required tension for each muscle by approximately half and significantly lowering the load. These results demonstrate that QDD-MM enables compact tendon-driven robots by allowing additional muscles to be added through modular connections and by using the muscle modules themselves as structural components.

C. Musculoskeletal Robot Experiment

Here, we construct the arm of a musculoskeletal humanoid using eight QDD-MMs and a 3D-printed musculoskeletal structure [21]. The purpose is to demonstrate integration of multiple identical modules with anatomical wire routing to actuate the scapula and upper arm together. The overall system and its motions are shown in Fig. 13. The eight QDD-MMs are connected both vertically and horizontally, resulting in a compact and space-efficient arrangement. By actuating these modules, we successfully achieve simultaneous movements of the scapula and the upper arm. The numbered images (1)–(3) show successive postures: the upper arm moves from a near-downward posture toward a more outward posture while the shoulder configuration changes. Although the motor units are currently located outside the body, our future plan is to integrate them within the body and construct a full musculoskeletal humanoid.

IV. CONCLUSION

In this study, we proposed QDD-MM, a simple and compact muscle module that utilizes quasi-direct-drive motors with the aim of further democratizing tendon-driven robots.

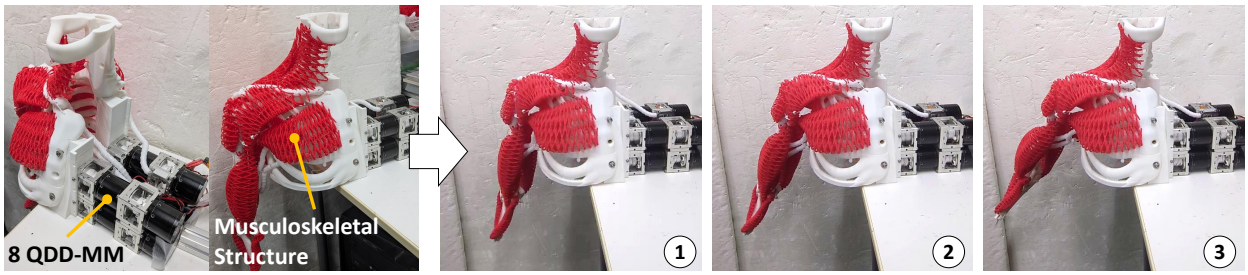


Fig. 13. Shoulder–arm prototype driven by eight externally mounted QDD-MMs. Left: module arrangement and musculoskeletal structure. Right, (1)–(3): successive postures showing the change in upper-arm orientation and shoulder configuration relative to the torso.

By leveraging recent advances in quasi-direct-drive motors, we were able to eliminate the need for tension sensors and greatly simplify the structure of conventional muscle modules, which rely on high gear ratios and dedicated sensing units. At the same time, QDD-MM achieves high backdrivability and fast actuation. As a result, hysteresis is significantly reduced, and muscle modules can be connected in parallel or in series, allowing the number of muscles to be freely increased and enabling the modules themselves to function as part of the robot's skeletal structure. These findings suggest that the characteristics of modern quasi-direct-drive motors are highly compatible with tendon-driven robotic systems. In future work, we plan to develop more complex tendon-driven robots using QDD-MM and to investigate optimization methods for muscle arrangement. We also intend to evaluate the durability of QDD-MM and to examine its maintainability under long-term operation.

ACKNOWLEDGMENT

This work was partially supported by JST Moonshot R&D Program Japan Grant Number JPMJMS263D.

REFERENCES

[1] H. G. Marques, M. Jäntsh, S. Wittmeier, O. Holland, C. Alessandro, A. Diamond, M. Lungarella, and R. Knight, "ECCE1: the first of a series of anthropomimetic musculoskeletal upper torsos," in *2010 IEEE-RAS International Conference on Humanoid Robots*, 2010, pp. 391–396.

[2] M. Jäntsch, S. Wittmeier, K. Dalamagkidis, A. Panos, F. Volkart, and A. Knoll, "Anthrob - A Printed Anthropomimetic Robot," in *2013 IEEE-RAS International Conference on Humanoid Robots*, 2013, pp. 342–347.

[3] Y. Asano, T. Kozuki, S. Ookubo, M. Kawamura, S. Nakashima, T. Katayama, Y. Iori, H. Toshinori, K. Kawaharazuka, S. Makino, Y. Kakiuchi, K. Okada, and M. Inaba, "Human Mimetic Musculoskeletal Humanoid Kengoro toward Real World Physically Interactive Actions," in *2016 IEEE-RAS International Conference on Humanoid Robots*, 2016, pp. 876–883.

[4] K. Kawaharazuka, S. Makino, K. Tsuzuki, M. Onitsuka, Y. Nagamatsu, K. Shinjo, T. Makabe, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Component Modularized Design of Musculoskeletal Humanoid Platform Musashi to Investigate Learning Control Systems," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2019, pp. 7294–7301.

[5] S. Hirose and S. Ma, "Coupled tendon-driven multijoint manipulator," in *1991 IEEE International Conference on Robotics and Automation*, 1991, pp. 1268–1275.

[6] H. Kobayashi, K. Hyodo, and D. Ogane, "On Tendon-Driven Robotic Mechanisms with Redundant Tendons," *The International Journal of Robotics Research*, vol. 17, no. 5, pp. 561–571, 1998.

[7] G. Endo, A. Horigome, and A. Takata, "Super Dragon: A 10-m-Long-Coupled Tendon-Driven Articulated Manipulator," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 934–941, 2019.

[8] T. Suzuki, M. Bando, K. Kawaharazuka, K. Okada, and M. Inaba, "SAQIEL: Ultra-Light and Safe Manipulator with Passive 3D Wire Alignment Mechanism," *IEEE Robotics and Automation Letters*, vol. 9, no. 4, pp. 3720–3727, 2024.

[9] S. Inoue, K. Kawaharazuka, T. Suzuki, S. Yuzaki, K. Okada, and M. Inaba, "CubiX: Portable Wire-Driven Parallel Robot Connecting to and Utilizing the Environment," in *2024 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2024, pp. 1296–1301.

[10] S. C. Jacobsen, H. Ko, E. K. Iversen, and C. C. Davis, "Control strategies for tendon-driven manipulators," *IEEE Control Systems Magazine*, vol. 10, no. 2, pp. 23–28, 1990.

[11] K. Koganezawa and M. Yamazaki, "Mechanical stiffness control of tendon-driven joints," in *1999 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1999, pp. 818–825.

[12] K. Kawaharazuka, M. Nishiura, Y. Toshimitsu, Y. Omura, Y. Koga, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Robust Continuous Motion Strategy Against Muscle Rupture using Online Learning of Redundant Intersensory Networks for Musculoskeletal Humanoids," *Robotics and Autonomous Systems*, vol. 152, pp. 1–14, 2022.

[13] S. Ohta, K. Hongo, Y. Nakanishi, I. Mizuuchi, and M. Inaba, "Improvement of performance for musculoskeletal robots by mountable actuator units," *Journal of Robotics and Mechatronics*, vol. 22, no. 3, pp. 391–401, 2010.

[14] Y. Asano, T. Kozuki, S. Ookubo, K. Kawasaki, T. Shirai, K. Kimura, K. Okada, and M. Inaba, "A Sensor-driver Integrated Muscle Module with High-tension Measurability and Flexibility for Tendon-driven Robots," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2015, pp. 5960–5965.

[15] K. Kawaharazuka, S. Makino, M. Kawamura, Y. Asano, Y. Kakiuchi, K. Okada, and M. Inaba, "Human Mimetic Forearm Design with Radioulnar Joint using Miniature Bone-muscle Modules and its Applications," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2017, pp. 4956–4962.

[16] J. Mi, W. Tong, Y. Ma, and X. Huang, "Design of a variable stiffness quasi-direct drive cable-actuated tensegrity robot," *IEEE Robotics and Automation Letters*, vol. 10, no. 9, pp. 8626–8633, 2025.

[17] S. Sawaguchi, T. Suzuki, A. Miki, K. Kawaharazuka, S. Yuzaki, S. Yoshimura, Y. Ribayashi, K. Okada, and M. Inaba, "Vlimb: A Wire-Driven Wearable Robot for Bodily Extension, Balancing Powerfulness and Reachability," in *2024 IEEE-RAS International Conference on Humanoid Robots*, 2024, pp. 851–857.

[18] B. Katz, J. D. Carlo, and S. Kim, "Mini Cheetah: A Platform for Pushing the Limits of Dynamic Quadruped Control," in *2019 IEEE International Conference on Robotics and Automation*, 2019, pp. 6295–6301.

[19] B. Deutschmann, J. Reinecke, and A. Dietrich, "Open source tendon-driven continuum mechanism: A platform for research in soft robotics," in *2022 IEEE International Conference on Soft Robotics*, 2022, pp. 54–61.

[20] M. Jäntsch, S. Wittmeier, K. Dalamagkidis, and A. Knoll, "Computed muscle control for an anthropomimetic elbow joint," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 2192–2197.

[21] S. Yoshimura, A. Miki, K. Miyama, Y. Sahara, K. Kawaharazuka, K. Okada, and M. Inaba, "Patterned Structure Muscle : Arbitrary Shaped Wire-Driven Artificial Muscle Utilizing Anisotropic Flexible Structure for Musculoskeletal Robots," in *2024 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2024, pp. 13 930–13 937.