

A Discreet Artificial Muscle for Elbow Flexion: Hook-Routed Cable Design, Quasi-Static Force Model and Qualitative Prototype Evaluation

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Abstract

People with weak arm muscles can use powered arm supports, but most are bulky and conspicuous. We describe a low-cost, motor-driven artificial muscle for elbow flexion that can be worn under a jacket. A NEMA 17 stepper motor on a shoulder brace winds fishing line onto a spool. Between an upper-arm band and a forearm band, the line passes back and forth through sewn-on steel hook-and-eye fasteners, forming a multi-strand tackle across the elbow. The prototype went through ten documented design iterations in a five-person student project (NTU EE5082, 2024). It was tested qualitatively: it raised and lowered the wearer’s forearm, was used while holding a jerrycan of unknown mass, and was worn by one volunteer in a single session. No assist force, efficiency or physiological effect was measured. To understand what the design can and cannot do, we build a quasi-static model of the elbow with the measured routing geometry, segment masses, and capstan friction at each hook. The model predicts that sliding friction strongly limits the gain of a hook tackle: with an assumed friction coefficient of 0.15, four strands give a lifting gain of 2.26 instead of 4. The same friction aids the device when it holds a position. With the motor torque the team assumed (0.2 N m) and a 20 mm spool, the device would supply about 82% of the torque needed to hold the forearm and hand at 90° while lifting, but up to several times that when holding. This asymmetry is consistent with the team’s observation that the device suits static support more than active movement. We correct an arithmetic error in the original capacity estimate (20.3 kg; the formula gives 2.04 kg), list the design levers that matter most (spool radius, motor torque, low-friction redirects), and propose a bench and user-test protocol that would turn these predictions into measurements.

1 Introduction

Arm weakness from neuromuscular disease, injury or fatigue makes everyday lifting tiring. Powered and passive arm supports exist, but rigid exoskeletons are heavy and visible, and many users do not want a device that marks them out. Soft, cable-driven exosuits move the actuator off the arm and transmit force through textiles and cables [2, 3]. The ETH Zurich Myoshirt, for example, assists shoulder elevation with a motor-shortened cable acting as an artificial tendon, and delayed fatigue in unimpaired users [1]. Its off-body actuator and control unit weighs about 4 kg, and its authors note that it must shrink further before it can be worn unobtrusively under clothing.

This paper documents a student prototype that set out to be small and discreet first. It assists only one joint, the elbow, and is built from hobby-grade parts: a stepper motor, a 3D-printed spool, fishing line, and hook-and-eye fasteners from a sewing kit. Our contributions are:

1. a description of the device and of the ten design iterations that led to it (Section 2);
2. a quasi-static force model of a hook-routed multi-strand tackle across the elbow, including capstan friction,

with open code (Section 3);

3. model predictions of support, travel and speed, and their sensitivity to motor torque and spool radius (Section 4);
4. an honest account of what the prototype showed, what it did not, and a correction to the original capacity estimate (Section 5).

We make no claim of clinical benefit or of novelty over prior cable exosuits. A prior-art search for hook-based tackle routing has not been done.

2 Device

Architecture. A NEMA 17 stepper motor (1.7 A, driven at 1/8 microstepping) sits on a base plate over a padded shoulder brace (Fig. 1a). A 3D-printed spool on its shaft winds monofilament fishing line, stated by the team to be rated at 17.5 kg. The line runs over the shoulder and down the front of the upper arm to a band set high on the arm, above the biceps; an anchor placed lower slipped down under load. Between this band and a forearm band, the line passes back and forth through sewn-on steel hook-and-eye fasteners and is tied off (Fig. 1b). Photographs show about four

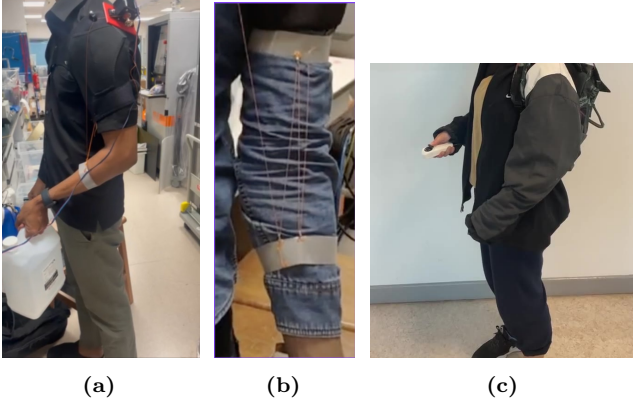


Figure 1: Prototype. (a) Final layout: stepper and spool on a base plate over a shoulder brace, line to a forearm band, holding a jerrycan of unknown mass. (b) Iteration 7: fishing line routed several times between sewn-on hooks on two bands across the elbow. (c) Concealment test: the device and its bag worn under a jacket (frame from video, face cropped).

Table 1: Documented design iterations.

#	Change
1–3	Finger cable, glove harness and pivot concepts
4	Cloth straps for comfort and a higher pulling limit
5	Shoulder strap as mounting platform, Velcro sizing
6	3D-printed pulley with bearings
7	Sewn hook-and-eye hooks with fishing line
8	Stepper motor does the pulling
9	Motor moved to the back on a base plate
10	Undersleeve for comfort

strands; the exact count was not documented. Velcro bands fit different arm sizes.

Control and safety. An Arduino UNO drives the stepper through a driver board. A handheld PS2 joystick raises or lowers the arm; an earlier two-button control confused the test user and was replaced. The default state is off, a software step count limits travel, a kill switch cuts the supply, and a fuse protects the circuit. An HC-06 Bluetooth link sent on/off and direction commands successfully; app-based data logging was not achieved.

Packaging. The electronics and a portable battery ride in a camera bag, or a backpack under a jacket (Fig. 1c). A thin undersleeve protects the skin.

Iterations. Table 1 summarises the ten iterations documented on the team’s blog [6]. The key transmission change was iteration 7: sewn-on hooks replaced 3D-printed pulleys with bearings. The team chose the hooks because they are hardened steel, smooth enough to act as a bearing analogue, light, easy to sew on and strong.

Side view, $\theta = 70^\circ$: n strands run between the two hook rows

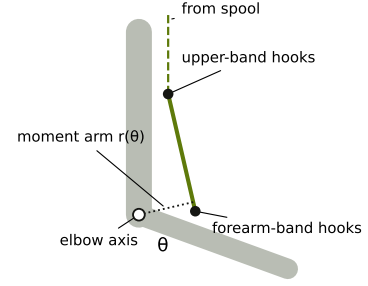


Figure 2: Planar model. The elbow is the origin; θ is flexion from the hanging arm. Strands run between the upper-band hooks U and forearm-band hooks $F(\theta)$; $r(\theta)$ is their perpendicular distance from the elbow axis.

3 Quasi-static model

Geometry. We model the arm in the sagittal plane with the elbow at the origin (Fig. 2). The upper hooks sit at $U = (h_u, d_u)$ with $d_u = 0.198$ m above the elbow and $h_u = 0.048$ m anterior. The forearm hooks sit $d_f = 0.085$ m along the forearm and $h_f = 0.037$ m anterior:

$$F(\theta) = d_f (\sin \theta, -\cos \theta) + h_f (\cos \theta, \sin \theta). \quad (1)$$

These dimensions match the schematic 3D model and the photographs; they are estimates, not measurements. All strands are treated as one line from U to F with length $L(\theta) = \|F - U\|$ and moment arm

$$r(\theta) = \frac{|U \times (F - U)|}{\|F - U\|}. \quad (2)$$

Gravity load. Forearm and hand masses follow Winter’s segment data [4] for an illustrative 70 kg adult: $m_f = 1.12$ kg with its centre of mass at $0.43 \ell_f$ ($\ell_f = 0.26$ m), and $m_h = 0.42$ kg at 0.31 m. A load m_L is held at $r_L = 0.33$ m. The torque the elbow flexors (or the device) must supply is

$$\tau_g(\theta) = g \sin \theta (m_f 0.43 \ell_f + m_h r_h + m_L r_L). \quad (3)$$

Tackle with hook friction. With n strands between the bands, an ideal tackle multiplies the motor-side line tension T_m by n . The line, however, slides around each hook rather than rolling over a pulley. By the capstan relation [5], tension changes by $e^{\pm \mu \phi}$ at each hook with wrap angle $\phi \approx \pi$ (a U-turn). When the motor lifts, friction opposes the line, and the force on the forearm band is

$$F_{\text{lift}} = T_m \sum_{k=0}^{n-1} e^{-\mu \pi k} = T_m G_{\text{lift}}(n, \mu). \quad (4)$$

When the motor holds still and the load tries to pull line out, static friction can act the other way, so the holding force is bounded by $G_{\text{hold}} = \sum_k e^{+\mu \pi k}$. We use $\mu = 0.15$ for nylon monofilament on polished steel as an assumption and vary it from 0.05 to 0.3.

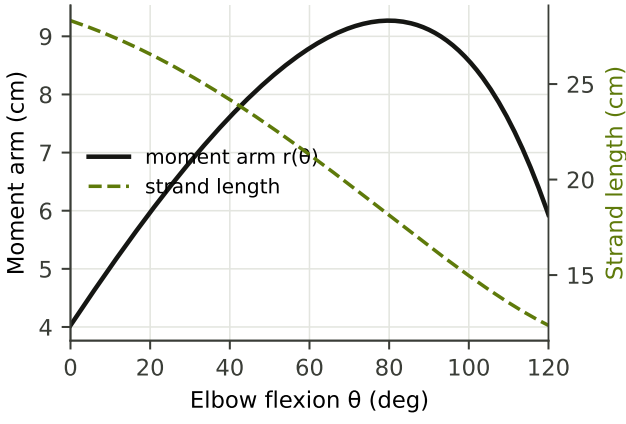


Figure 3: Moment arm and strand length against flexion. The moment arm grows from 4.0 cm with the arm straight to 9.1 cm at 90°, as the strands stand off from the inner elbow, then falls.

Drive. The motor-side tension is $T_m = \tau_m / r_s$ for shaft torque τ_m and spool radius r_s . The team’s own capacity calculation used $\tau_m = 0.2$ N m; we use it as the baseline and also consider 0.4 N m, closer to the holding torque of common 1.7 A NEMA 17 motors. The spool radius was not documented; we take $r_s = 20$ mm and sweep 8 to 50 mm. The device torque and the largest hand load it can balance are

$$\tau_d(\theta) = \frac{\tau_m}{r_s} G(n, \mu) r(\theta), \quad (5)$$

$$m_{L, \max}(\theta) = \frac{\tau_d(\theta) - \tau_g(\theta)|_{m_L=0}}{g r_L \sin \theta}. \quad (6)$$

A negative $m_{L, \max}$ means the device cannot carry the forearm and hand on its own. The line wound onto the spool to flex from 0 to θ is $n[L(0) - L(\theta)]$.

4 Model results

Leverage. The strand bundle has a moment arm of 4.0 cm with the arm hanging, 8.8 cm at 60° and 9.1 cm at 90° (Fig. 3). This is comparable to the biceps moment arm. Because the line lies on the arm surface, it never passes through the joint, so leverage does not vanish at full extension.

Demand. The gravity torque peaks at 90° (Fig. 4): 2.51 N m for the forearm and hand alone, 5.74 N m with 1 kg in the hand and 18.7 N m with 5 kg. Demand and leverage both peak near 90°, so that is the critical posture.

Friction caps the tackle. Figure 5 shows the effective gain. With $\mu = 0.15$, two strands give 1.62 and four give 2.26 rather than 4; eight strands reach only 2.60. At $\mu = 0.3$ four strands give 1.60. Adding strands beyond about four mostly adds line travel and wear, not force. In holding, the bound for four strands is 9.28.

Support. With the baseline drive the motor-side tension is 10 N. Figure 6 gives the device torque as a share

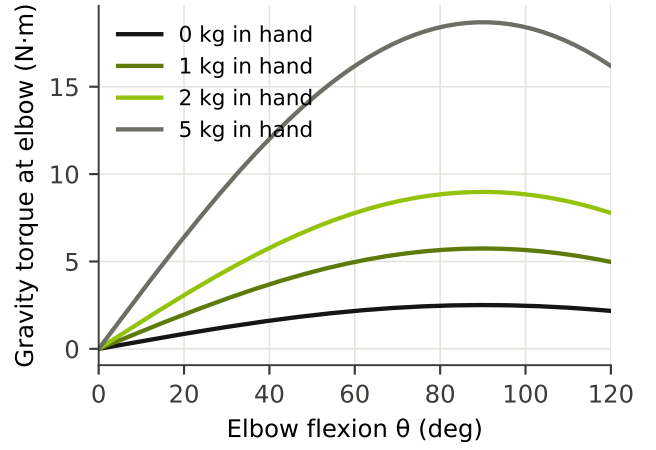


Figure 4: Gravity torque at the elbow for different loads in the hand (70 kg adult, Winter segment data).

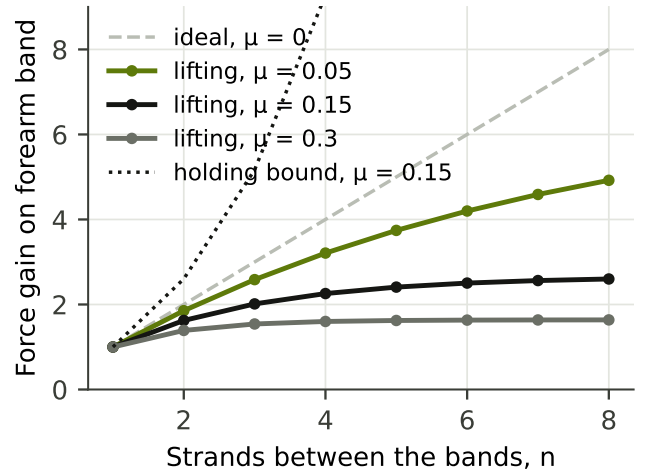


Figure 5: Force gain of an n -strand hook tackle. Sliding friction at each U-turn makes the lifting gain saturate. Holding is bounded by friction acting in the device’s favour.

of the arm-weight torque. At 90° while lifting, one, two and four strands supply 36, 59 and 82% of what the forearm and hand need; the user’s own muscles must supply the rest and any load. While holding, four strands can in the best case supply up to 3.4 times the arm-weight torque, enough in principle to hold about 1.8 kg in the hand. Doubling motor torque to 0.4 N m lets four strands lift about 0.5 kg at 90°; halving the spool radius to 10 mm as well raises this to about 1.8 kg (Fig. 7).

Travel and speed. Each strand shortens by 11.8 cm from 0 to 90°, so four strands need 47 cm of line on the spool (Fig. 8). At one spool revolution per second with a 20 mm spool this takes 3.8 s; one strand takes 0.9 s. The tackle trades speed for force one-for-one in the ideal case and worse than that with friction.

Line strength. Holding 5 kg at 90° with four strands loads each strand to about 51 N, a safety factor of 3.3 on the stated 171.7 N line rating. Line strength is not the binding constraint; motor torque and friction are.

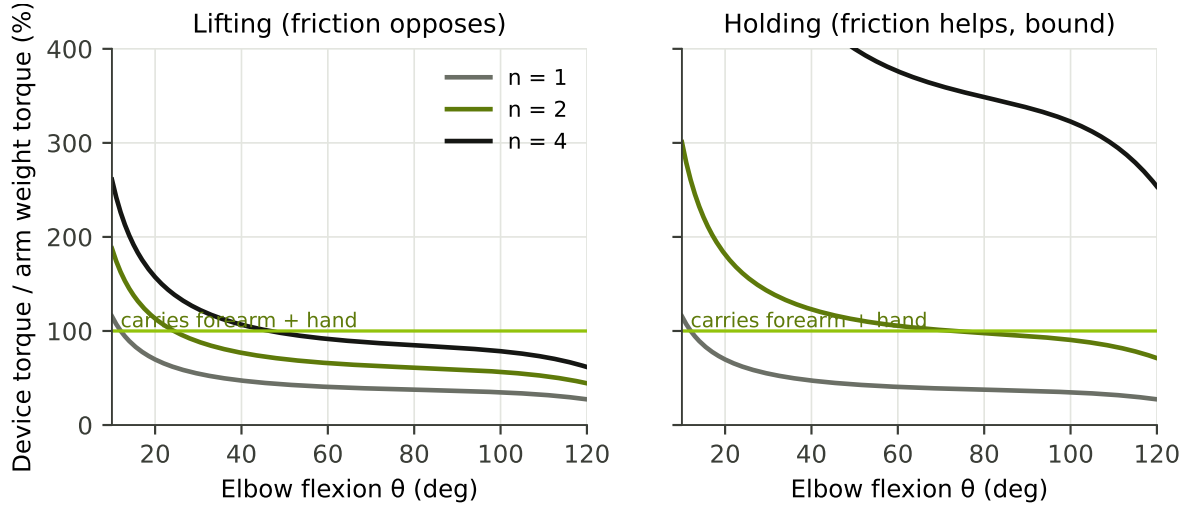


Figure 6: Device torque as a percentage of the torque needed to hold the forearm and hand, for $n = 1, 2, 4$ strands ($\tau_m = 0.2$ N m, $r_s = 20$ mm, $\mu = 0.15$). Above the 100 % line the device can also take load in the hand. Left: lifting. Right: upper bound when holding.

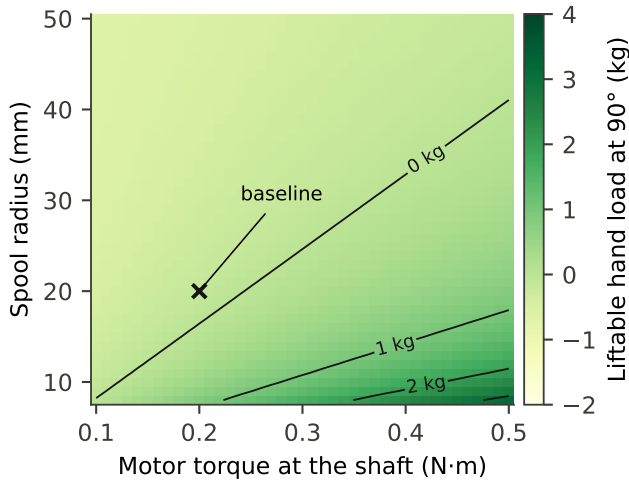


Figure 7: Hand load the device alone could lift at 90° with four strands and $\mu = 0.15$, against motor torque and spool radius. The cross marks the baseline.

5 Prototype evaluation

All testing was qualitative. Table 2 separates what was shown from what was not.

Demonstrations. Videos show the wearer raising and lowering the forearm with the joystick, the shoulder unit flexing the arm with the line visible, use while holding a jerrycan, and a volunteer wearing the device under a jacket with the electronics in a backpack. The jerrycan’s contents and mass were not recorded, so these clips show function, not capacity.

Arm load measurement. Using a handheld luggage scale, the team recorded a peak of 7.6 kg-force needed to lift the arm while holding an object. This characterises the demand on an assist, not the force the device produced. The point of attachment and the object were not documented.

Table 2: Evidence from the prototype.

Item	Status
Forearm raised and lowered by joystick	shown on video
Used while holding a jerrycan	shown; mass unknown
Worn under a jacket with bag	shown on video
Peak force to lift arm with object, luggage scale	7.6 kg, team reading
Single volunteer session (n = 1)	qualitative
Bluetooth on/off/direction	worked
Assist force, torque, efficiency	not measured
Muscle activity or fatigue	not measured
System mass	target <3 kg; not weighed

User session. One adult volunteer with a sprained arm wore the device in a single session. Her forearm moved up and down; she was surprised it could carry the jug but said it did not feel strong, since it hung on fishing line. The two-button control confused her, so it was replaced by the joystick, and long wires and a mains lead restricted movement. This is a single qualitative observation.

Build observations. During development the stepper stalled when the arm was pressed against it, and a teammate estimated it could handle about 4 kg at the line. The team concluded that the device suits static support more than active movement.

Correcting the capacity estimate. The original slides computed a lifting capacity of $(0.2 \times 5) / (0.05 \times 9.81) = 20.3$ kg. The expression evaluates to 2.04 kg. It also assumed a 5:1 planetary gearbox that was later rejected for being too slow, a spool radius that was not the one built, and it describes force at the spool, not at the hand. We withdraw the 20.3 kg figure.

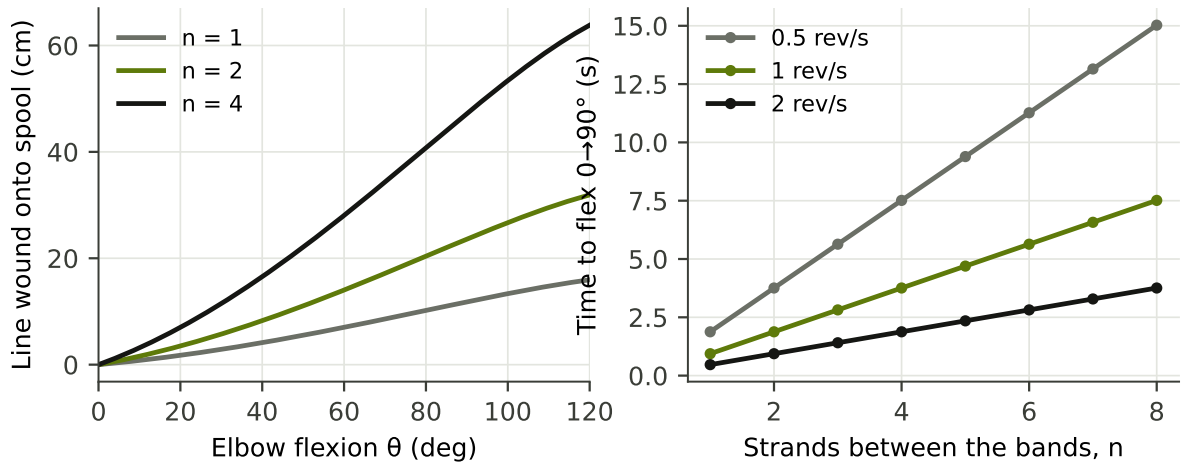


Figure 8: Left: line wound onto the spool against flexion. Right: time to flex from 0 to 90° for spool speeds of 0.5–2 rev/s ($r_s = 20$ mm).

6 Discussion

Why it is better at holding than lifting. The model offers a mechanism for the team’s observation. Every hook the line slides around costs force when lifting but can supply force when holding. With four strands and $\mu = 0.15$, the lifting gain is 2.26 and the holding bound is 9.28, a four-fold asymmetry. A stepper’s holding torque also exceeds its torque at speed. Both effects favour static support. This is a hypothesis; it needs a bench measurement.

Design levers. Figure 7 shows that the spool radius is as strong a lever as the motor: halving it doubles line tension at the cost of speed. Real low-friction redirects (small bearing pulleys, or PTFE-lined hooks) would recover most of the ideal gain, at some cost in bulk. A geared motor raises torque but was rejected here for speed; Fig. 8 shows how much speed the tackle already consumes.

Relation to prior work. Cable exosuits for the elbow and shoulder are established [3, 2, 1], and those systems have been measured in user studies. Ours has not, so we do not compare performance. The Myoshirt assists a different joint and reports physiological outcomes in ten unimpaired participants and two with impairments. Our design’s distinguishing choices are concealment-first packaging and a tackle built from sewn hook-and-eye fasteners; whether the latter is new is unknown.

7 Limitations

The geometry, segment masses, friction coefficient, motor torque and spool radius are estimates. The model is planar and quasi-static: it ignores line stretch, soft-tissue compression under the bands, band migration, motor dynamics and the user’s own muscle activity. There is one qualitative user session. None of the model’s predictions has been checked against a measurement.

8 Proposed validation

1. **Bench rig.** A mannequin arm with an encoder at the elbow and a load cell in series with the line; measure lifting and holding gain for $n = 1$ –6 with hooks and with bearing pulleys, which gives μ directly.
2. **Drive.** Measure pull-out torque against step rate for the motor and spool as built.
3. **Wear.** Weigh the system and measure band migration under load.
4. **Users.** A within-subject study (about 10 participants, with ethics approval) of biceps EMG and time to fatigue while holding a load at 90°, device on versus off.

9 Conclusion

A shoulder-mounted stepper, a spool, fishing line and sewn-on hooks make a light, concealable elbow assist that demonstrably moves the forearm. A simple force model shows that, as built, it is unlikely to lift much beyond the arm’s own weight, because sliding friction at the hooks caps the tackle’s gain, but that the same friction helps it hold a posture. That matches what the team saw. The model gives clear, testable design targets: smaller spool, more motor torque, and lower-friction redirects.

Author contributions

Sreeram Vasanth: team lead, market research and roadmap, spool and coupler design, hook-and-line arm arrangement and anchoring, kill switch, hardware, wiring and housing; force model and this manuscript. Liao Kheng Wee Bryan: hardware, printed mounts, housings and pulley-system iterations, safety. Dai Jingyang: electronics, stepper driver wiring and Arduino code, step limit, Bluetooth-to-motor link. Shreya Jindal: procurement and budget, Bluetooth app, sensor research. Sarah Tan Jun Le: communications and blog, usability session. Dr Ho: supervision.

Acknowledgements

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Code and data

Model code, figures and the 3D model: <https://github.com/vasanth sreeram/discreet-artificial-muscle>. Project page: <https://vas.sh/research/discreet-artificial-muscle>.

References

- [1] A.-M. Georgarakis, M. Xiloyannis, P. Wolf, R. Riener. A textile exomuscle that assists the shoulder during functional movements for everyday life. *Nature Machine Intelligence* 4, 574–582, 2022. doi:10.1038/s42256-022-00495-3
- [2] M. Xiloyannis et al. Soft robotic suits: state of the art, core technologies and open challenges. *IEEE Transactions on Robotics* 38(3), 1343–1362, 2022.
- [3] M. Xiloyannis, D. Chiaradia, A. Frisoli, L. Masia. Physiological and kinematic effects of a soft exosuit on arm movements. *Journal of NeuroEngineering and Rehabilitation* 16, 29, 2019.
- [4] D. A. Winter. *Biomechanics and Motor Control of Human Movement*, 4th ed. Wiley, 2009.
- [5] J. L. Meriam, L. G. Kraige. *Engineering Mechanics: Statics*. Wiley (flexible belts and the capstan relation).
- [6] Exomusculature team. EE5082 project blog, 2024. <https://blogs.ntu.edu.sg/ee5028-2024-g01/>