Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.39212

A Guide-Pulley-Free Staggered Cable-Driven Reduction Mechanism for an Elbow Exoskeleton

Hanwen Zhang[1,*], Sirui Luo[2], Qiquan Liang[3]

[1]Wyoming Seminary, Kingston, USA
[2]Guangzhou Foreign Language School, Guangzhou, China
[3]Guangdong Country Garden School, Foshan, China
**Corresponding Author. Email: 389877526@qq.com*

Abstract. This paper presents a guide-pulley-free, staggered cable-driven reduction mechanism for an elbow exoskeleton and other limited-rotation assistive devices. The design uses a motor, a small helical-groove shaft, one continuous cable, and a single integrated sector-shaped output part. The cable wraps around the small shaft about six times, and its two ends travel directly to two height-offset arc grooves on the sector part, so that the two cable segments cross when viewed from above without touching. No guide pulley, tensioning pulley, slider, or spring appears anywhere in the cable path. The small shaft has an effective diameter of 18 mm and the sector output part an effective diameter of 210 mm, giving a theoretical reduction ratio of about 11.67:1. Cable tension is set by wrapping and clamping each cable end onto a screw fixed on the sector part, eliminating any separate tensioning component. The small shaft is printed in carbon-fibre-reinforced PLA and the remaining structure in PLA by additive manufacturing. A working prototype has been built and tested for basic function, verifying bidirectional motor rotation, a 160-degree output range, and stable cable tension during motion; output torque, efficiency, weight, noise, and fatigue life remain to be measured.

Keywords: elbow exoskeleton, capstan drive, cable-driven transmission, sector pulley, additive manufacturing

1. Introduction

Elbow exoskeletons are wearable devices that support or assist elbow flexion and extension for people with muscle weakness, nerve injury, or post-surgical rehabilitation needs [1]. Because a compact motor cannot supply the torque required at the joint on its own, such a device needs a transmission that reduces motor speed and increases torque while keeping the mechanism light enough to wear.

Cable-driven transmissions are a common choice for this purpose. A motor turns a small drum, and a cable wrapped around the drum carries motion to a larger driven part. Compared with gear trains, cable transmissions can provide low backlash, a simple structure, and low weight [2]. However, many existing cable-driven designs still require guide pulleys, tensioning pulleys, sliders,

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.39212

or springs to keep the cable in the correct path and under the correct tension, which adds weight, introduces failure points, and complicates assembly.

This paper presents a cable-driven reduction mechanism that removes these extra guide parts entirely. The device uses a motor, a small helical-groove shaft, a single continuous cable, and one sector-shaped output part. The cable winds several times around the shaft, and its two ends travel directly to two height-offset grooves on the sector part; because the segments are offset along the shaft axis, they can cross without touching, and clamping the cable ends onto screws sets the tension without a separate tensioner. Since the elbow is a hinge joint with a limited rotation range, the output part needs only a sector rather than a full wheel, which reduces weight and material.

The remainder of the paper reviews related work (Section 2), describes the mechanism design (Section 3), reports the prototype and its validation (Section 4), discusses benefits and limitations (Section 5), and concludes (Section 6).

2. Related work

Several transmission approaches connect a compact motor to the joint of an elbow exoskeleton. Gear trains, including harmonic drives, provide a high reduction ratio in a small space but must mesh accurately, add weight at the joint, and generate noise. Cable-driven exoskeletons instead transmit force through a cable, which keeps the actuator away from the joint; for example, the CURER upper-limb rehabilitation exoskeleton routes Bowden cables through flexible sheaths to transfer torque from remote actuators to the elbow and wrist [3]. Capstan, or cable-friction, drives transmit torque through friction between a cable and a rotating drum, and some existing capstan exoskeletons still rely on guide pulleys, an independent lead-screw tensioner, or two separate cables to control the path and tension.

The capstan principle is well established in robotics: a cable wrapped around a rotating drum transmits torque through friction, achieving low backlash and low inertia. Hwangbo et al. demonstrate a single-stage cable-pulley transmission with no backlash and low inertia in the Capler-Leg, a highly dynamic legged robot [4]. This study confirms the underlying friction-transmission principle used here; this work does not claim that principle as new.

Cable-driven transmissions are well suited to joints with a limited rotation range, such as the elbow and wrist. Buongiorno et al. present a three-degree-of-freedom wrist exoskeleton with a tendon-driven differential transmission for rehabilitation and teleoperation [5]. For the printed structure, polylactic acid (PLA) is easy to print but brittle, while carbon-fibre-reinforced PLA (CFR-PLA) improves the stiffness and strength of fused deposition modelling parts [6]; CFR-PLA is used here for the cable-contact shaft.

A prior-art search over patent databases (CNIPA, WIPO PATENTSCOPE, Google Patents), academic literature, and public engineering sources compared the present design with closely related cable-driven work. Existing systems rely on cable-driven differentials, Bowden cables, or single-stage cable-pulley transmissions with a separate guiding structure. None combines a single continuous cable, two height-offset segments feeding directly into two grooves on one integrated sector output part, and no guide pulley or separate tensioner.

DOI: 10.54254/2755-2721/2026.39212

3. Mechanism design

3.1. System architecture

The mechanism combines a motor, a small helical-groove shaft, a single continuous cable, an integrated dual-groove sector output part, and a forearm bracket, as shown in Fig. 1. The motor turns the small shaft in either direction; the cable, wound around the shaft, carries this motion to the sector output part through friction. The sector output part is mounted coaxially with the elbow joint and drives the forearm bracket directly.

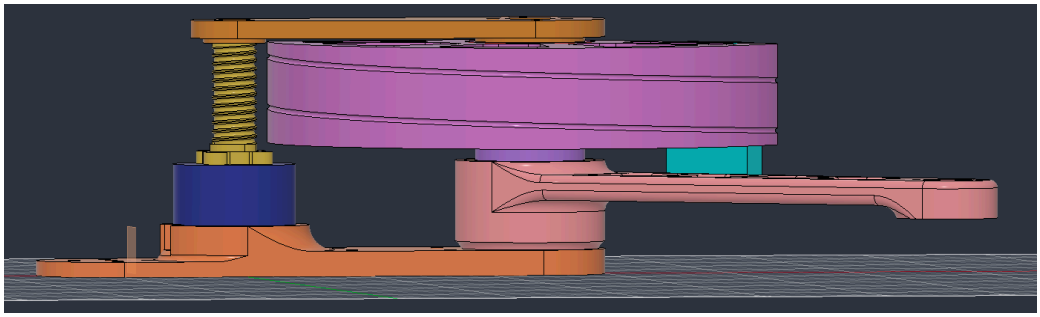


Figure 1. Overall side view of the mechanism

3.2. Staggered dual-cable-path design

The single continuous cable leaves the small shaft at two points, one from the top and one from the bottom of the wound section, forming two cable segments that both travel toward the sector output part. In a plan view the paths of these two segments cross (Fig. 2). If the segments were at the same height they would rub during motion, adding friction, wear, and noise. To avoid this, the two segments are separated along the shaft axis by approximately the height of the wound section (about six wraps); because of this axial offset, they pass at different heights where their paths cross and never touch. This removes the need for any guide pulley or separator part.

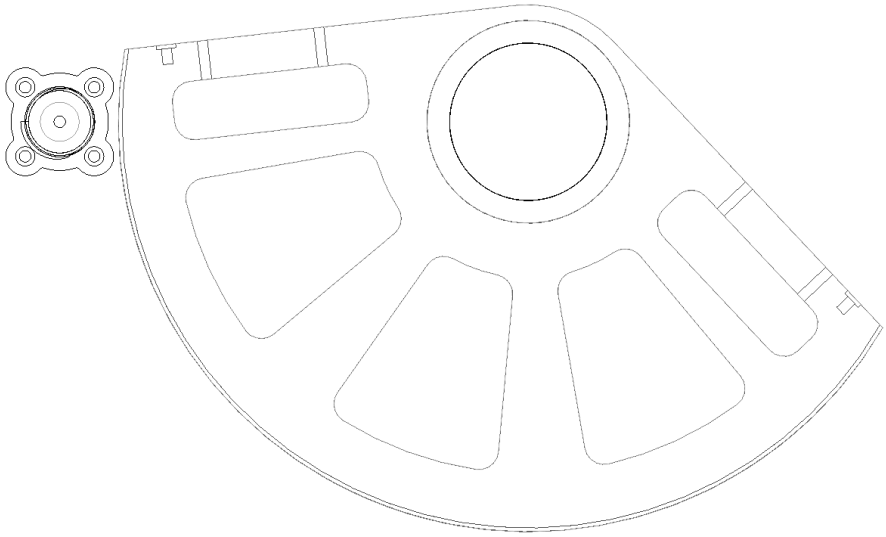


Figure 2. Top view of the staggered cable path and sector output part

DOI: 10.54254/2755-2721/2026.39212

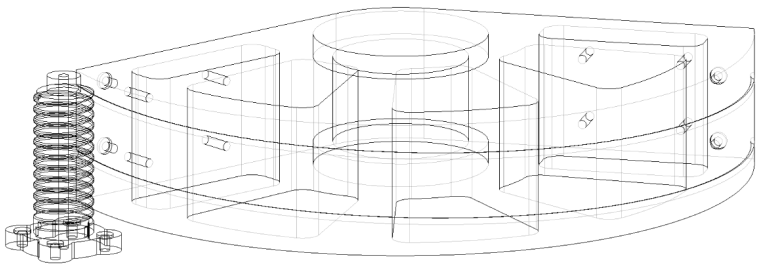


Figure 3. Guide-pulley-free direct cable path and dual-groove sector output part

3.3. Integrated dual-groove sector output component

The sector output part is a single printed component that combines several functions: two arc-shaped grooves at different heights carry the two cable segments, lightening holes reduce weight, and the part also includes fixing points for the two cable ends, a coaxial mounting hole for the elbow joint, and a connection feature for the forearm bracket (Fig. 4). Integrating these functions reduces the number of separate components that would otherwise be needed to hold the cable, mount the joint, and connect the bracket.

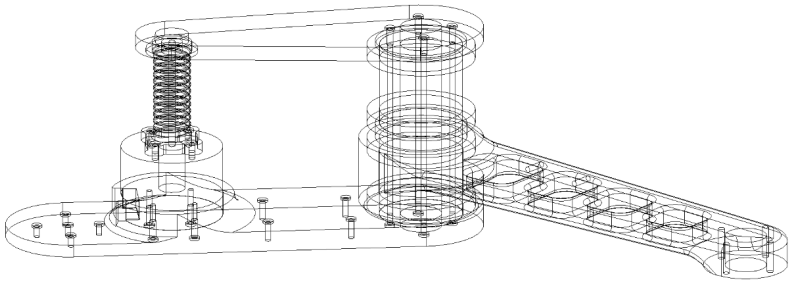


Figure 4. Integrated dual-groove sector output component

3.4. Reduction ratio and cable pretensioning

In a capstan drive the reduction ratio is set by the ratio of effective diameters. With a small-shaft effective diameter of 18 mm and a sector effective diameter of 210 mm, the theoretical reduction ratio is

$$i = D_out / D_in = 210/18 \approx 11.67 \tag{1}$$

giving about 11.67 turns of the small shaft per turn of the output part and about 11.67 times the input torque at the output, neglecting friction losses. Table 1 lists the main design figures. The cable is wrapped about six times around the shaft, whose helical groove keeps the wraps in order and increases the contact angle and hence the maximum friction force before slip. Each end of the cable is wrapped around a screw on the sector part and clamped against it; tightening the screws before clamping sets the tension, so no lead screw, slider, or spring is needed.

DOI: 10.54254/2755-2721/2026.39212

Table 1. Main design figures of the mechanism

Small-shaft diameter	Sector-pulley diameter	Wraps on shaft	Reduction ratio	Output angle
18 mm	210 mm	~6 turns	11.67:1	160°

4. Prototype and validation

A working prototype was built from PLA structural parts, with the small shaft printed in CFR-PLA, using a Bambu Lab X2D printer and a 0.8 mm Dyneema DM20 braided cable. The prototype has completed functional checks verifying bidirectional motor rotation, a 160-degree range of motion at the sector output part, and stable cable tension during motion (Fig. 5); Table 2 summarises the results.



Figure 5. Completed prototype worn on the arm during a functional check

Table 2. Completed validation results

Item	Current status	Validation result
Design files	Fusion 360 project files, STEP models	Completed
Direction of rotation	Motor forward and reverse rotation	Verified
Range of motion	Sector output part completes 160-degree motion	Verified
Cable state	Cable stays under tension and in its groove during motion	Verified

Output torque, transmission efficiency, weight, running noise, positioning accuracy, and fatigue life have not yet been measured. These measurements, together with a quantitative comparison against gear-based and Bowden-cable transmissions of similar size, form the main direction for future work.

5. Discussion

The design offers several practical benefits. Because the sector output part covers only the joint angle actually used, it uses less material than a full wheel, and because it is mounted coaxially with

DOI: 10.54254/2755-2721/2026.39212

the joint it can drive the forearm bracket directly. The structure is manufactured by additive manufacturing in PLA and CFR-PLA, which suits design verification, small-batch production, and rapid design changes; the sector part and bracket can be resized for different users and ranges of motion. Compared with designs using multi-stage gears, guide pulleys, or an independent tensioner, the mechanism uses fewer parts and has a more direct assembly, and the friction-based drive should, in principle, reduce the meshing noise of gear transmissions and free the motor from having to sit on the elbow axis.

These benefits are, however, still provisional. The prototype demonstrates the principle but has not yet been characterised for torque, efficiency, weight, noise, accuracy, or fatigue life, so the expected advantages over gear and Bowden designs remain to be confirmed quantitatively. The friction behaviour and long-term wear of the CFR-PLA cable-contact surface under sustained load also require further testing.

6. Conclusion

This paper presented a guide-pulley-free, staggered cable-driven reduction mechanism for an elbow exoskeleton. A single continuous cable is wound around a small helical-groove shaft and its two ends travel directly to two height-offset grooves on one integrated sector output part, without passing through any guide pulley, tensioning pulley, slider, or spring; cable tension is set by end-wrap clamping onto screws fixed on the sector part. With 18 mm and 210 mm effective diameters, the mechanism provides a theoretical reduction ratio of about 11.67:1 and a 160-degree output range.

The contribution is an engineering combination rather than a new basic principle: cable-friction reduction, helical-groove guidance, single-cable synchronised winding, and sector output pulleys each exist separately in the literature, but their combination into a single-cable, dual-height-offset, guide-pulley-free sector drive was not found as a complete match in the sources reviewed. A prototype has verified bidirectional rotation, the 160-degree range, and stable cable tension; measuring torque, efficiency, weight, noise, accuracy, and fatigue life is the main direction for future work, along with extending the same architecture to other limited-rotation joints in rehabilitation and wearable robotics.

References

[1] Chen, T., Casas, R., & Lum, P. S. (2019). An elbow exoskeleton for upper limb rehabilitation with series elastic actuator and cable-driven differential. *IEEE Transactions on Robotics, 35*(6), 1464–1474. https://doi.org/10.1109/TRO.2019.2930915

[2] Mazumdar, A., et al. (2017). Synthetic fiber capstan drives for highly efficient, torque controlled, robotic applications. *IEEE Robotics and Automation Letters, 2*(2), 554–561. https://doi.org/10.1109/LRA.2016.2646259

[3] Qian, W., et al. (2023). CURER: A lightweight cable-driven compliant upper limb rehabilitation exoskeleton robot. *IEEE/ASME Transactions on Mechatronics, 28*(3), 1730–1741. https://doi.org/10.1109/TMECH.2022.3224423

[4] Hwangbo, J., Tsounis, V., Kolvenbach, H., & Hutter, M. (2018). Cable-driven actuation for highly dynamic robotic systems. *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 8543–8550. https://doi.org/10.1109/IROS.2018.8593569

[5] Buongiorno, D., Sotgiu, E., Leonardis, D., Marcheschi, S., Solazzi, M., & Frisoli, A. (2018). WRES: A novel 3 DoF WRist exoskeleton with tendon-driven differential transmission for neuro-rehabilitation and teleoperation. *IEEE Robotics and Automation Letters, 3*(3), 2152–2159. https://doi.org/10.1109/LRA.2018.2810943

[6] Veerapuram, S., Jagannathan, S. S., & Navaneethakrishnan, L. (2024). Process parameters optimization for 3D printed carbon fiber reinforced PLA composites. *2024 2nd International Conference on Recent Trends in Microelectronics, Automation, Computing and Communications Systems (ICMACC)*, 790–793. https://doi.org/10.1109/ICMACC62921.2024.10894034