A Low-Cost Upper Limb Exoskeleton Assistive Device Based on Elbow Torque Feedback

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Project Website: *https://exoskeleton-club.github.io/ULETF/*.

APPENDIX

A. Details of the exoskeleton structure design

To demonstrate the structural design details of the upper limb exoskeleton, we present an explosion diagram for display. The overall structure explosion diagram of the upper limb exoskeleton is shown in **Fig. A1**. During the exoskeleton structural design process, several components are skeletonized to achieve lightweighting of the overall system. On the basis of meeting the weight requirement, in order to further improve the structural performance and support future upgrades and enhancement designs, topology optimization techniques can be introduced to achieve the optimal trade-off between strength and mass.

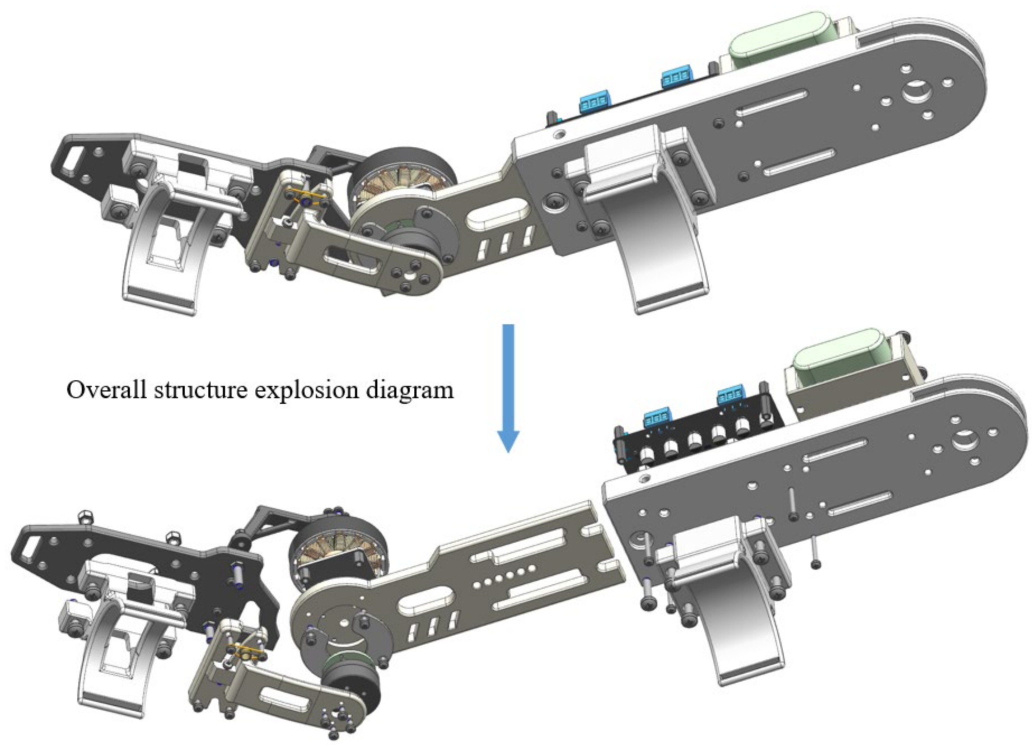

Fig. A1 An explosion diagram of the overall structure of the upper limb exoskeleton.

B. Physical test of the exoskeleton device

To validate the effectiveness of the dual-motor torque feedback system at the elbow joint, we performed physical tests on the upper limb exoskeleton. In these tests, the exoskeleton was suspended, and torque was manually applied to rotate the drive motor, allowing us to observe and evaluate the assistive motor's response and performance.

We recorded and analyzed the observational results from the physical tests of the exoskeleton elbow joint, with specific details presented in **Fig. A2**. The results show that the rotation directions and angles of the drive motor and the assistive motor are the same, and the corresponding rotations of the elbow joint remain consistent, which can achieve the synchronous torque feedback effect.

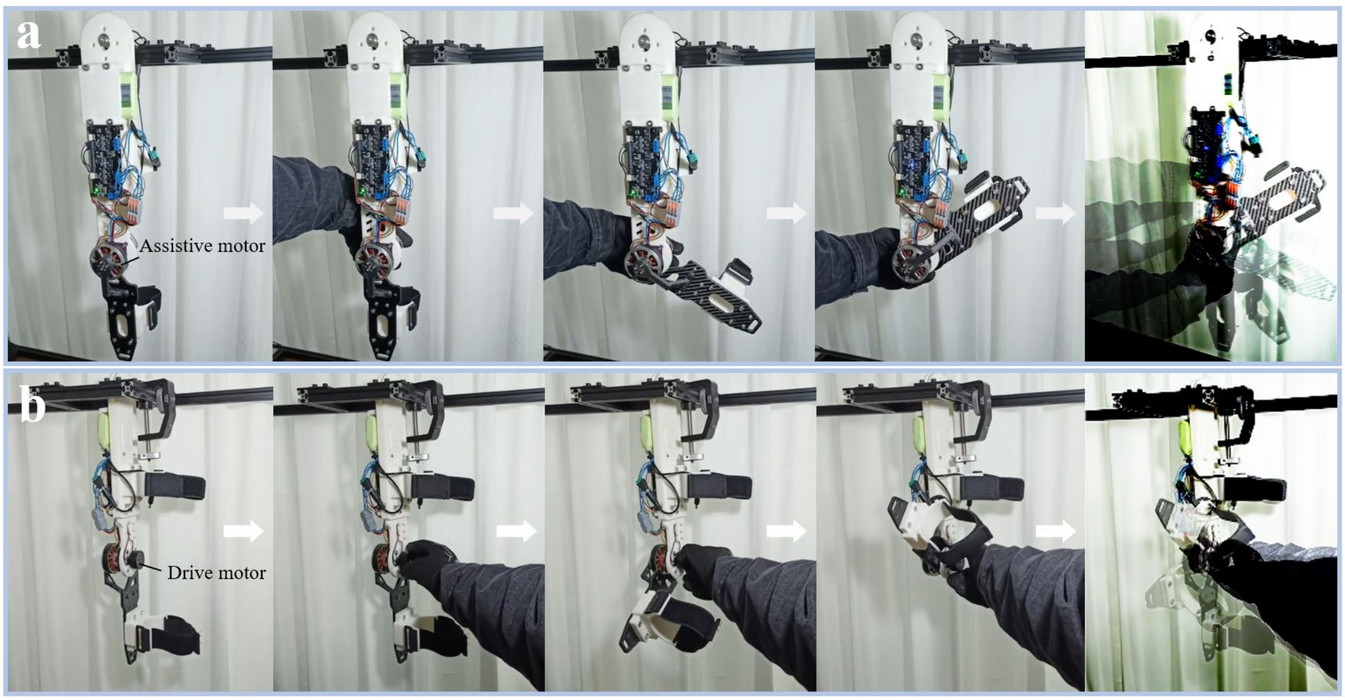

Fig. A2 Physical testing of elbow joint torque feedback in the upper limb exoskeleton. (a) Effect as tested without drive motor connector assembled (Front view). (b) Effect as tested with no drive motor connector assembled (Side view).

Furthermore, the drive motor connector was integrated into the exoskeleton system, and a horizontal placement test was conducted on the complete upper limb device. In the experiment, slight lifting of the forearm strap was used to evaluate system response. Owing to the torque feedback control strategy of the dual-motor system—which aims to minimize the angular difference between the two motors—and the preset angular offset of the drive motor in its initial state, even minor forearm movements trigger immediate torque feedback. This causes the auxiliary motor to synchronously rotate in the same direction as the driving motor, thereby generating assistive torque on the forearm plate. This torque is ultimately transmitted to the user's upper limb, enabling motion assistance. In addition, a floating rubber band was incorporated into the drive motor connector to provide a compliant buffer between the connector and the forearm plate. This design helps to absorb minor rotational mismatches between the driving and auxiliary motors, thereby enhancing the smoothness of elbow assistance and improving the overall comfort of human-robot interaction. The results of the horizontal placement test are illustrated in **Fig. A3**.

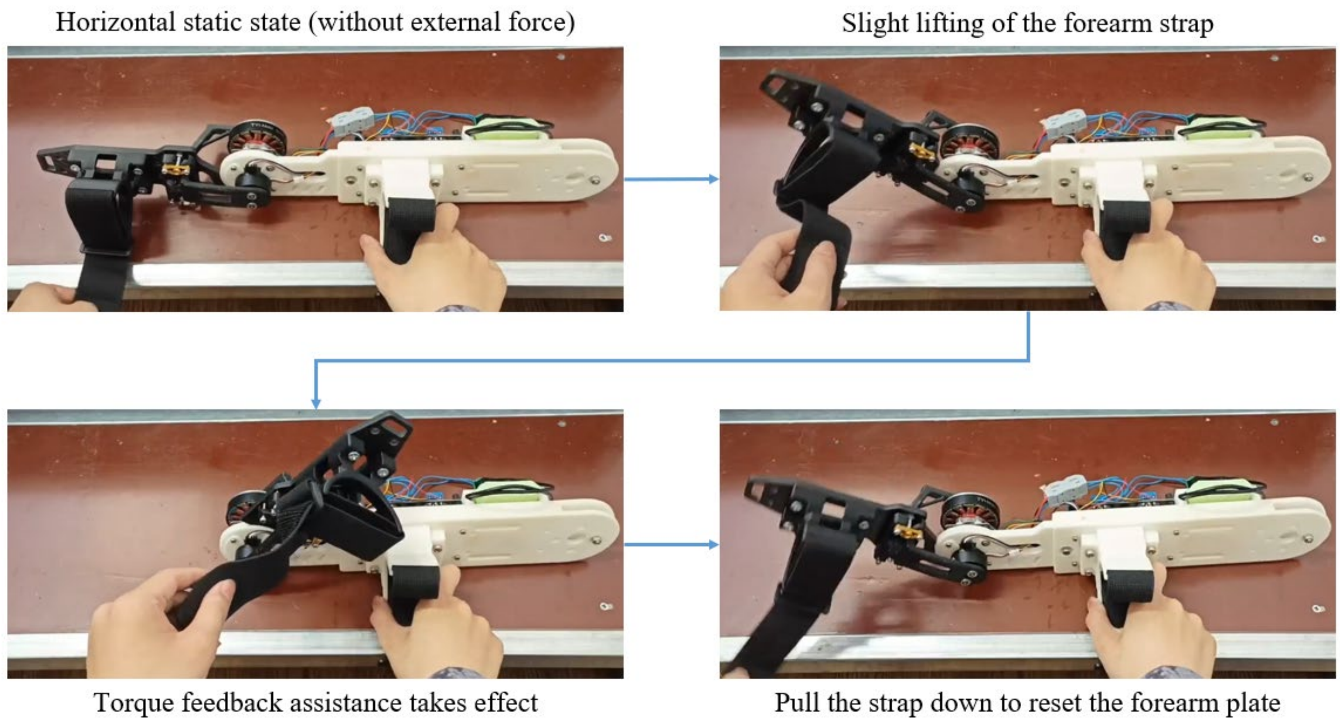

Fig. A3 The torque feedback test process in the horizontal placement state.

At the same time, the elastic cushion structure (floating rubber band) in the drive motor connector was tested during the torque feedback test in the horizontal position (see **Fig. A4**). The drive motor connector is designed with a circular groove, through which a small range of rotation is realized. The floating rubber band assembly forms a kinematic coupling with the set screw in the forearm plate, which can effectively realize the dynamic damping and elastic buffer function.

Fig. A4 Verification test of the elbow buffer structure of the upper limb exoskeleton.