Interactive Muscle Contractions for Soft Robotics

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***Abstract*— For soft robotics towards human-friendly and functional interaction, being flexible yet strong enough to carry large loads is one of the most challenging goals. The state-of-the-art technologies may not realise this flexible-yet-strong feature effectively, because the current stiffness control mechanisms increase the strength of a soft structure in the price of losing its flexibility. To coordinate this conflict, we reviewed biological hydrostatic skeletons and found a possible underlying mechanism, namely interactive muscle contractions. The newly identified mechanism reveals that topologically different muscle contractions can enable shape/deformation-independent load-carrying capability which can preserves both flexibility and strength of soft robots. The proposed interactive muscle contractions mechanism may generalise and explain many biological observations and be used as the starting point for building up soft robotics.**

I. Background

The bending deformation demonstrated via the flexible microactuators by Suzumori in the late 1980s [1] is now the most widely and implicitly recognised design philosophy in soft robotics. Influenced by this bending idea, soft robotics has walked an amazing journey through transferring nature's inspiration and exploring human-friendly interaction [2]. Nevertheless, the development of soft robotics today is deviating from an early goal, being *flexible yet strong* enough to carry large loads, which was originally inspired by elephant trunks as they could lift and manipulate masses of up to 300 kg [3].

II. The Architectural Transmission Approach to the Load-Carrying Problem of Soft Robotics

Many stiffness control studies have been conducted to strengthen soft robots [4]. Those solutions can be placed into two categories, omnidirectional or direction-specific. The omnidirectional solutions are to increase overall structural stiffness, which includes raising internal chamber pressures [5] and adding extra hard materials such as granular jamming [6] and layer jamming [7]. Their fundamental drawback is the variable stiffness mechanisms themselves hinder deformations; consequently, the deformations have to add extra actuations for compensation, thus largely degrading motion smoothness and energy efficiency. For direction-specific solutions, the current studies consider direct chamber inflation [8], [9]. Although soft robots made in this way can result in rapid motions, they are very easy to buckle due to inherent compliance.

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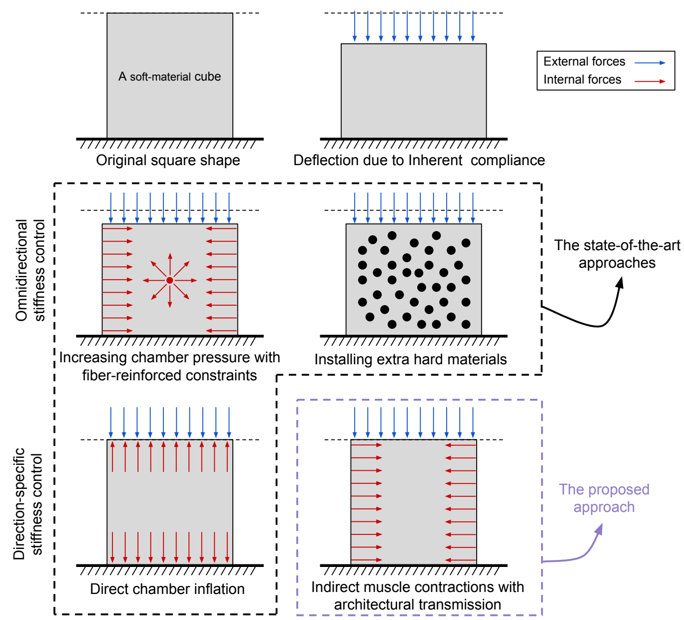

Fig. 1. Different approaches of undertaking loads in soft robotics. Beside using chamber inflation directly, the state-of-the-art approaches consider increasing internal pressure or adding extra stiffening mechanisms. Inspired by the biological architectural gear transmission study [10], we chose to use indirect muscle contractions to counteract external forces.

Uniquely, we chose to strengthen soft robots according to the biological architectural gear transmission study [10]; Figure 1 briefly explains its difference from the current approaches. For the architectural transmission approach, it largely preserves motion agility as its stiffness control is direction-specific; meanwhile, because this approach relies on contractile actuation and force transmission induced by the constant volume property, the resulted soft structure is more stable than its inflatable counterparts.

III. The Interactive Muscle Contraction Mechanism

Recently we found interactive muscle contractions mechanism can implement the architectural gear transmission for soft robotics. Different from Kier's biological muscular hydrostats study that identified the individual relation between muscle arrangements and deformation modes such as bending, torsion, and elongations [11], our new mechanism concerns the joint interactive effects of all muscle arrangements. For a muscular hydrostat, when its topology of muscle arrangements is set up properly, it can obtain full controllability at any shape; this implies that, if there is no actuation limit, such a full-control muscular hydrostat can

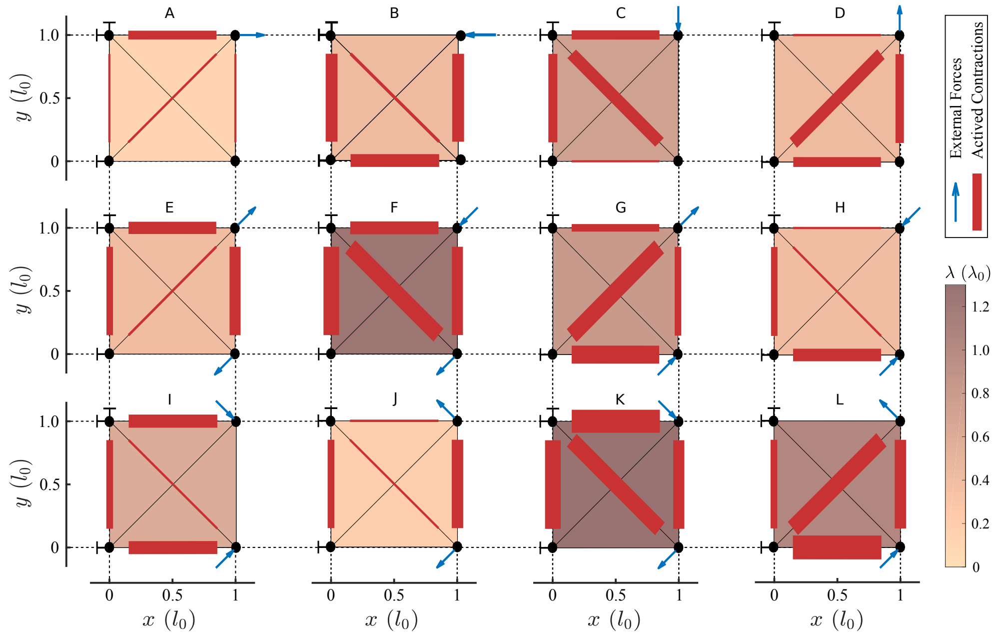

Fig. 2. For a 2-dimensional full-control muscular hydrostat that includes longitudinal, transverse, and oblique muscles, the interactive muscle contraction mechanism can counteract all possible external loads while maintaining the initial square shape. Activated muscles are coloured red and their widths show proportionally the strengths of contraction. The internal pressure is indicated by λ.

perform desired deformation at all loading conditions. For biological muscular hydrostats like elephant trunks, the new mechanism also suggests that it is the force control of muscle contractions that causes deformation and stiffness change simultaneously .

Figure 2 illustrates the interactive muscle contractions on a 2-dimensional muscular hydrostat. For a system of this kind, we proved mathematically that its full controllability requires a pair of longitudinal muscles, a pair of transverse muscles, and a pair of oblique muscles. As shown in Figure 2, actuating a certain set of muscles can decouple loads from corresponding directions; this explains how we implement the proposed architectural transmission approach highlighted in Figure 1.

Technically, the proposed interactive muscle contraction mechanism can be seen as a generalisation of Kier's muscular hydrostats study [12] and an extension to Suzumori's bending actuator design [1].

IV. Consistence with rigid-link robotics

Interestingly, the interactive muscle contraction mechanism shows consistence with rigid-link robotics; in a reverse way, a manipulator needs to use dedicate force control to realise compliance. This reciprocal relation may imply deep theoretical connections between the two separately studied fields today.

V. Summary and future work

According to the biological architectural gear transmission, we presented the interactive muscle contraction mechanism. The new mechanism can realise shape-independent load-carrying capability, thus leading to an improved solution to stiffening soft robotics. Theoretically, the newly proposed mechanism tends to generalise Kier's muscular hydrostat model, extend Suzumori's bending actuator design, and connect to rigid-link robotics. Next, we plan to research this new mechanism in 3-dimensional space.

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