INTRODUCTION

The so-called multi-articular musculotendons couple torque production across joints because they cross several degrees-of-freedom (DOFs) of a limb. There is much debate on whether the function and control differs for mono- and bi-articular musculotendons [4]. To expand this dialogue, I highlight some biomechanical aspects of multi-articular finger musculotendons. I conclude it is useful to consider these aspects before drawing conclusions about the neural selection of coordination patterns.

A SIMPLE FINGER MODEL

Consider a simple 2-joint, 5-musculotendon planar finger. Tendon routing produces moment arms $r_{ij}$ at DOF $i$ for musculotendon $j$ (Fig. A), which combined with the level of muscle force determine the contribution of each musculotendon force to joint (i.e., DOF) torques $\tau_1$ and $\tau_2$. This contribution leads to a vector in “torque space,” Fig. B [2, 5, 7]. The net joint torques are the resultant vector from the addition of the torque vectors from active musculotendons, Fig. D.

RESULTS AND DISCUSSION

I. For this model to be versatile at nonsingular finger postures, it should be able to produce static fingertip force vectors in every direction in the plane, Fig. A [2, 5, 7]. Given that fingertip force vectors are obtained by mapping net joint torque vectors through the Jacobian $J$ of the model, versatility is only possible if the musculature can produce net joint torque vectors in all quadrants of the torque space. That is, the feasible torque set (FTS) of the finger must span portions of all quadrants (Fig. C). The FTS defines all possible net joint torque vectors that could be produced by a group of musculotendons. The FTS is obtained by finding all possible positive linear combinations in torque space. E.g., FTS1,2 includes all possible torque vectors $m_1$ and $m_2$ can produce; and FTS1,2,3,4,5 is the total FTS for all muscles (Fig. C).

II. Every musculotendon, no matter how weak, contributes uniquely to the size and shape of the fingertip feasible force set. Thus, the impairment or rehabilitation of any musculotendon will change the size and shape of the feasible force set [7]. This challenges notions of musculotendon “redundancy” by making it difficult to decide which musculotendon we would rather do without—and suggests means to quantify and counteract impairment in partial paralyses [1].

III. Multi-articular musculotendons efficiently enlarge the total FTS. For example, $m_4$ can by itself span large sections of quadrant IV, which would otherwise need 2 dedicated musculotendons (Figs. C&D). Interestingly, this tendon cross-over (flexor first and then extensor) is a defining anatomical feature of the extensor mechanism. Greater coverage of quadrant IV can only enlarge the feasible force set of the fingertip. Interestingly, these cross-over musculotendons (lumbrical and palmar
interosseous) produce index fingertip force in directions useful to oppose the thumb during grasp [6]. This begins to explain the known finger impairment when the extensor mechanism is disrupted [3]. While the alternative cross-over tendon route is possible, the associated fingertip forces would be directed roughly opposite to those needed for grasp, which I speculate may not have as strong an evolutionary advantage.

And [IV]. Co-contraction (i.e., simultaneous activation of agonists and antagonists) at some finger DOFs is often not an option, but a consequence of multiarticular tendon routing. Co-contraction is seen graphically as a reversal along a DOF in the vector addition needed for net joint torque production. For example, producing the net joint torque vector 1 using m3, m4 and m5 must reverse direction one DOFs (wide bars on coordinate axes, Fig. D). Fig. E shows how only in FTS 1,2, FTS 3,4 and FTS 3,5 is it possible to achieve a net joint torque vector without reversing direction, e.g., torque vector 2. Redundancy is seen graphically as the possibility to reach any point inside FTS 1,2,3,4,5 via multiple vector additions. While points inside FTS 1,2, FTS 3,4 and FTS 3,5 can be reached both with and without co-contraction, co-contraction is unavoidable anywhere else in FTS 1,2,3,4,5. Thus versatile static fingertip force production requires co-contraction.

The FTS approach is only a linear approximation to the finger’s torque capabilities, and its results are sensitive to tension-dependent nonlinearities in moment arms and/or possible neural synergies. Nevertheless, it provides insight into the attributes of multi-articular musculotendons. I suggest that our understanding “bi-articular” musculotendons can extended by also considering the “tri-“ and “tetra-“ articular musculotendons of the fingers.

REFERENCES

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