SIMPLE FINGER MOVEMENTS REQUIRE COMPLEX COORDINATION OF EXCURSIONS AND FORCES ACROSS ALL MUSCLES

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INTRODUCTION

Producing accurate slow finger movements is critical to manipulation—and inaccurate finger movements are a hallmark of neurological diseases. Numerous studies have described the kinematics of able and pathological finger movements (e.g., (Dennerlein et al. 1998; Kamper and Rymer 2001; Littler 1973; Santello et al. 1998; Weiss and Flanders 2004)). This short report is, to our knowledge, the first complete simultaneous description of the force and excursion of all tendons that produce a coordinated finger flexion movement. We used computer-controlled motors to drive cadaveric index finger tendons to have direct access to the mechancial variables necessary to produce finger motion. This avoids the pitfalls of EMG and computational models, which cannot yet accurately estimate tendon excursion and force, or the role of skin and joint structures. This novel approach serves as the foundation for new research directions to understand the robustness of finger movement to neuromuscular dysfunction, and promote the design of novel robotic manipulators, prostheses and functional electrical stimulation schemes.

METHODS

Experimental preparation

We resected fresh frozen cadaver arms at the mid-forearm level and dissected them to reveal the proximal end of the insertion tendons of all seven muscles controlling the index finger (Valero-Cuevas et al. 2000): flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor indicis proprius (EIP), extensor digitorum communis (EDC), first lumbrical (LUM), first dorsal interosseous (FDI), and first palmar interosseous (FPI). We fixed the specimen rigidly to a tabletop using an external fixator (Agee-WristJack, Hand Biomechanics Lab, Inc., Sacramento, CA), and we tied and glued (Vetbond Tissue Adhesive, 3M Inc., St. Paul, MN) the proximal tendons to Nylon cords attached to rotational motors, Fig. 1A. Motors were controlled using a LabVIEW Real-time controller (PXI-8183 National Instruments, Austin, TX) and custom-written software. The motors could be programmed to operate in three control modes: *force control* – a desired tendon force is maintained regardless of tendon excursion, *position control* – a desired

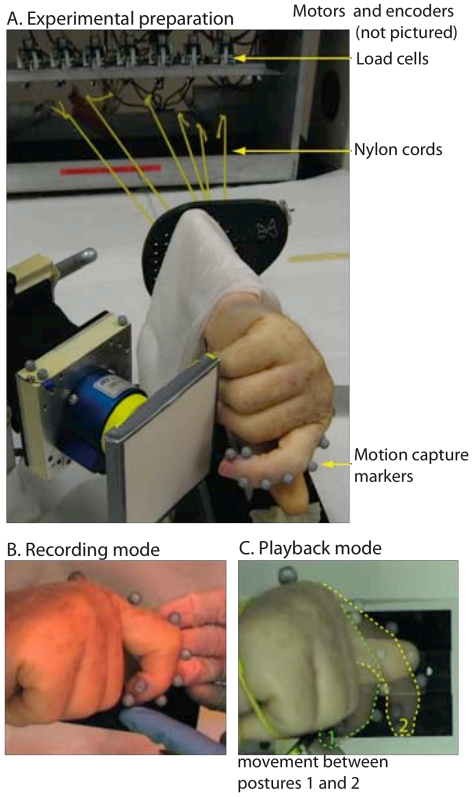

Fig. 1: Experimental preparation used to record a finger tapping movement and to play it back.

excursion is produced, regardless of the required force, and *tunable spring control* – the applied force is proportional to the difference in excursion from a set-point. Encoders mounted on the motors recorded tendon excursion, while load cells mounted between motors and tendons recorded tendon force.

Experimental procedure

The experiment had two phases: recording and playback. In the recording phase, motors were operated in force control with a desired tendon tension of 5 N (same for all tendons). The experimenter moved the finger through a simulated tapping movement (Venkadesan and Valero-Cuevas 2008), while we recorded the resulting tendon excursions (Fig. 1B). In the playback phase, the motors were controlled as stiff tunable springs (spring constant 5 N/mm for all tendons), with the time history of recorded tendon excursions played back as spring-length set points. This control caused the finger to replicate the desired finger movement, which we played back ten times in series to measure repeatability.

RESULTS AND DISCUSSION

We found that producing the recorded tapping movement ten times in playback generated a consistent pattern of tendon excursions and tensions (Fig. 1C). Moreover, we found that, to replicate the movement, a complex pattern of excursion and forces emerged at all tendons (Fig. 2). Whereas simply pulling manually on one or two of the tendons generated a movement approximating tapping, the realistic movement requires specific excursions and forces. These requirements arise from the biomechanical constraints. For example, the time history of unique tendon excursions (where all tendons must retain a tonic tension and cannot go slack) is defined by the time history of joint angles by the equation

$$\dot{s}(t) = R^T(q(t))\dot{q}(t)$$

where the transpose of the (angle-dependent) moment arm matrix $R^T(q(t))$ maps uniquely from joint angle changes to tendon excursions. While the baseline tendon tensions are free parameters (i.e., level of co-contraction), we see that the relative changes in tendon tensions follow a complex patterns not completely coupled to the kinematics; likely because they are governed by complex strain energy changes resulting from the necessary

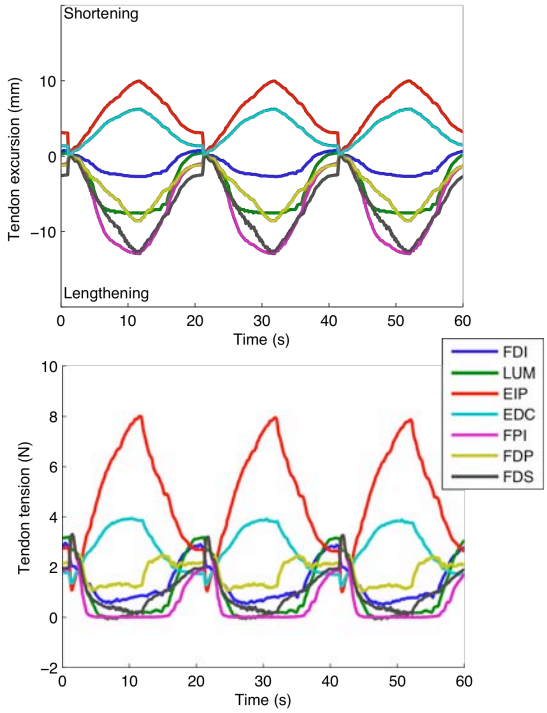

Fig. 2. Tendon excursions and tensions for the last three repetitions of the simple tapping movement.

eccentric and concentric contractions of our simulated muscles. Further study will examine the robustness of these coordination patterns to neuromuscular dysfunction.

CONCLUSIONS

We find that producing a repeatable tapping movement requires complex eccentric/concentric muscle contractions, suggesting that even simple natural movements are generated by the complex balance of activity in all muscles.

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