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Effects of task dynamics on coordination of the hand muscles and their adaptation to targeted muscle assistance

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ABSTRACT

Dynamic characteristics of a manual task can affect the control of hand muscles due to the difference in biomechanical/physiological characteristics of the muscles and sensory afferents in the hand. We aimed to examine the effects of task dynamics on the coordination of hand muscles, and on the motor adaptation to external assistance. Twenty-four healthy subjects performed one of the two types of a finger extension task, isometric dorsal fingertip force production (static) or isokinetic finger extension (dynamic). Subjects performed the tasks voluntarily without assistance, or with a biomimetic exotendon providing targeted assistance to their extrinsic muscles. In unassisted conditions, significant between-task differences were found in the coordination of the extrinsic and intrinsic hand muscles, while the extrinsic muscle activities were similar between the tasks. Under assistance, while the muscle coordination remained relatively unaffected during the dynamic task, significant changes in the coordination between the extrinsic and intrinsic muscles were observed during the static task. Intermuscular coherence values generally decreased during the static task under assistance, but increased during the dynamic task (all p-values < 0.01). Additionally, a significant change in the task dynamics was induced by assistance only during static task. Our study showed that task type significantly affect coordination between the extrinsic and intrinsic hand muscles. During the static task, a lack of sensory information from musculotendons and joint receptors (more sensitive to changes in length/force) is postulated to have resulted in a neural decoupling between muscles and a consequent isolated modulation of the intrinsic muscle activity.

1. Introduction

The architecture of the hand musculotendons is complex. Many tendons cross more than one joints, and their kinetic actions differ significantly from one to another (Valero-Cuevas et al., 1998; Lee et al., 2008). Some finger musculotendons are interconnected within a tendinous network (Garcia-Elias et al., 1991; Valero-Cuevas et al., 2007), and to surrounding ligaments (Young and Rayan, 2000), which affect the transformation of tendon force to joint moment. Cross-sectional areas (CSA) of the hand muscles vary considerably (An et al., 1985), reflecting variation in their force-generating capacity. Moment arms of hand musculotendons and their excursions are also significantly different from one another (An et al., 1983). When a task is performed, coordination of these muscles must be determined by mapping their distinct biomechanical outputs (multi-joint moments) to the task domain to satisfy the goal, such as interjoint coordination during movements (Cole and Abbs, 1986; Darling et al., 1994; Kuo et al., 2006), or the interaction with the environment at the fingertip – in particular, the fingertip force magnitude/direction (Milner and Dhaliwal, 2002) or its stiffness (i.e., endpoint stiffness; Balasubramanian and Matsuoka, 2008, 2009).

Even for the tasks that require the same biomechanical inputs (joint moments), however, muscle coordination can be different depending on their dynamic conditions (static vs. dynamic). The dynamic conditions affect the amount of sensory information processed during tasks; while sensory receptors in muscles/tendons can detect/carry both static (magnitude) and dynamic (rate of change) senses, they are generally more sensitive to dynamic information (Proske and Gandevia, 2012). Mechanoreceptors in skin/

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joints mainly respond to joint movements, while only a limited amount of position information is carried (Edin, 1990). Additionally, the architecture of the hand musculotendons may influence when they activate; intrinsic muscles can produce large forces (large CSA), but the resulting joint motions are relatively small (Jacobson et al., 1992). Conversely, extrinsic hand muscles are mainly responsible for movement generation (Schieber, 1995) – while they mainly provide stability during static force production, their activities do not correlate well with force magnitudes (Milner and Dhaliwal, 2002). These observations suggest that the task dynamics could significantly affect the hand muscle coordination, but such task effects are yet to be examined in details.

Furthermore, hand muscle coordination can also be modulated under external dynamics, whether such dynamic effects were either anticipated (Johansson and Westling, 1988) or unanticipated (Cole et al., 1984). Sometimes manual tasks need to be performed with assistance, such as in the robot-assisted rehabilitation for stroke survivors, to reinforce their diminished muscle capacity (Balasubramanian et al., 2010). Coordination of the hand muscles, and its adaptation to assistance, would be of significant importance for patients who need to restore the pattern of motor control before injuries (Lee et al., 2013). Due to the aforementioned biomechanical/physiological factors, it is highly likely that pattern of motor adaptation to external assistance is affected by task dynamics (e.g., isometric vs. movement training).

In this study, we aimed to examine the effects of task dynamics on the coordination of hand muscles and its adaptation to an external assistance. Finger extension was examined due to its importance in stroke rehabilitation (Kamper et al., 2003). Two types of this task, isometric dorsal fingertip force production (static) and isokinetic finger extension (dynamic), were performed without assistance, or with a biomimetic exotendon device that provided targeted assistance to extrinsic hand extensor muscle (extensor digitorum communis; EDC). Different measures of the motor control/adaptation, as well as task performance, were compared. We hypothesized that a significant difference in the muscle coordination patterns will be observed between static and dynamic tasks. We further hypothesized that the task type will also significantly affect the adaptation of muscle coordination to an external assistance. We anticipated that, as more sensory information is available under dynamic condition, the task dynamics will be preserved under dynamic condition, while a significant change may be observed under static condition.

2. Methods

2.1. Subjects

Twenty-four healthy, right-handed subjects (21–43 yrs) participated in the study. Twelve subjects (5 males) performed isometric tasks (Task 1), and the other twelve (8 males) performed isokinetic tasks (Task 2). The experimental protocol was approved by the institutional review boards of the MedStar Health and the Catholic University of America; written informed consent was obtained prior to participation.

2.2. Target task

For Task 1, subjects produced a dorsal fingertip force (Fig. 1a). The force sensor were adjusted such that they could maintain 30° flexion at the distal interphalangeal (DIP) joint, 45° flexion at the proximal interphalangeal (PIP) joint, and 30° flexion at the metacarpophalangeal (MCP) joint of their index finger. For Task 2, subjects performed ‘timed’ finger extension movements (Fig. 1b). The target finger posture was selected considering the force-length relationship of the extrinsic extensor muscle (EDC), as the joint moment production capacity of the EDC muscle was found to significantly decrease as the finger joints fully extend (Kamper et al., 2006) or fully flexed (due to decreased joint-to-fingertip distance). Previous studies adopted joint angles similar to our target posture during fingertip force production (Valero-Cuevas, 2000; Lee et al., 2018). Subjects were asked to perform the task only with the index finger (Task 1) or the index and middle fingers (Task 2), but they were not required to restrain the movements of the other fingers.

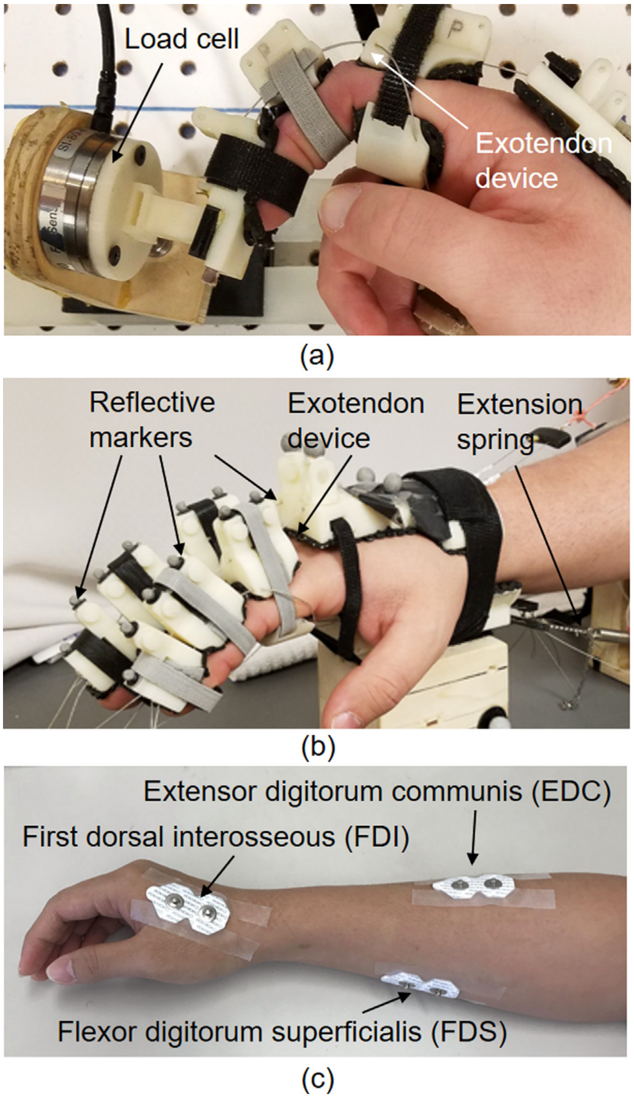


Fig. 1. Experimental setup with the exotendon device providing targeted assistance to the extrinsic finger extensor tendon (EDC); (a) Task 1 (isometric); (b) Task 2 (isokinetic); (c) Electrode placement. Note that the forearm was set in neutral rotation (Task 1) or in pronation (Task 2) before the electrodes were placed.

2.3. Instrumentation

Subjects wore a biomimetic device (BiomHED; Lee et al., 2014a; Fig. 1) that provided assistance during experiments. An exotendon that mimics the anatomy of the EDC tendon ($\mathrm{ET_{EDC}}$) were pulled by an electric motor (Maxon AG, Switzerland) to provide targeted assistance. During Task 2, another exotendon replicating the extrinsic finger flexor ($\mathrm{ET_{FDP}}$) was connected to an extension spring, providing resistance during movements.

A 6 degree-of-freedom load cell (Mini40; ATI Industrial Automation, Apex, NC) was used to record fingertip forces, and an 8-camera motion capture system (Osprey System; Motion Analysis Corp., Santa Rosa, CA) to record finger movements. Spherical retro-reflective markers (8 mm in diameter) were adhered to palpable landmarks, including dorsal aspects of DIP, PIP, MCP, and cartpometacarpal joints of the index/middle fingers (Zhang et al., 2003).

Three pairs of disposable, self-adhesive silver/silver chloride surface electrodes were used to record electromyography (EMG) data from EDC (1st compartment), flexor digitorum superficialis (FDS; 1st compartment), and first dorsal interosseous (FDI) (Myosystem 1400A; Noraxon Inc., Scottsdale, AZ).

2.4. Experimental protocol

Each subject was seated in an adjustable chair with elbows rested on padded supports, and with forearm stabilized by Velcro straps.

Subjects first created maximum activations, for the normalization purpose, by performing the following tasks: finger extension (EDC), finger flexion with the DIP joint extended (FDS), and index finger abduction (FDI). Subjects performing Task 1 maintained the posture used during the force production, while neutral posture was used for those performing Task 2.

The task setup (target force level for Task 1; resistance for Task 2) and assistance levels were determined by a preliminary testing with a subset of subjects (n = 3) to match the effort levels (muscle activation) between the tasks. Specifically, the intensity of the two tasks (target force; resistance) was selected so that the activation of the major agonist muscle for the task (EDC) was at approximately 25% of the maximal contraction for each subject during task performance.

The following procedures were then implemented for each group (Fig. 2). For details of the experimental protocol, see Appendix A.

(1) Task 1 (isometric): Subjects first produced maximum voluntary dorsal fingertip force (MVF), which determined their target force F_{tar} (40% of the MVF). The assistance level for each subject was then determined under assistance-only condition (AO).

Two assistance conditions (A_0: unassisted; A_1: assisted) were tested while subjects produce target fingertip force (force development phase: 3-s; force maintenance phase: 3-s). The assistance level was increased to the predetermined assistance level during the development phase. The custom GUI provided visual cues regarding the fingertip force and the timing.

(2) Task 2 (isokinetic): For each subject, resistance provided by the flexor exotendon (ET_{FDP}) was adjusted based on the finger segment length and gender, and the resulting activation level of the EDC muscle during movements was approximately 20% to 30% of their maximal level. The assistance level was then determined under AO; the assistance level was determined as the force to achieve about 40% of the full finger extension.

Two assistance conditions (A_0/A_1) were then tested as subjects performed ‘timed’ finger extension movements. Similar to Task 1, the assistance level was increased to the predetermined assistance level during the movement phase. The GUI provided visual cues regarding the timing with a sliding bar with marks.

For both tasks, ten trials were recorded per condition, and the order of the conditions was randomized across subjects. Approximately 30 s of rest were given between the trials, and a 10-min break between the conditions.

2.5. Data analysis

The following variables were computed for data analysis. See Appendix B for details.

(1) **Mean Activation Level (MAL)**: MALs of the three muscles (MAL_i; $i = 1$: EDC, 2: FDS, 3: FDI) were estimated.
(2) **Co-contraction ratio (CCR)**: CCR of the three muscle pairs, EDC-FDS (CCR_{12}), FDS-FDI (CCR_{23}), and EDC-FDI (CCR_{13}) were estimated from their activation profiles.
(3) **Intermuscular coherence integral (ICI)**: EMG-EMG coherence between the three muscle-pairs was computed.
(4) **Change in MAL, CCR, ICI**: For the MAL, CCR, ICI values, their relative changes under the assistance were computed (log change in percent) to account for high between-subject variability.
(5) **Task dynamics:** Three different measures were computed for each task:
    a. Task 1
        - Task performance: Task error ε_F
        - Goal-irrelevant output: The angular deviation of the force from the normal direction.
        - Biomechanical efficiency: Joint moments required to produce the fingertip force.

    b. Task 2
        - Task performance: Total extension angle of the three joints.
        - Goal-irrelevant output: Temporal coordination of the PIP and MCP joints.
        - Biomechanical efficiency: Joint moments required to produce the movement patterns.

(6) **Statistical analysis:** A multivariate analysis of variance was then implemented (SPSS; IBM Corp., Armonk, NY). For the task dynamics variables, univariate analyses of variance were used.

3. Results

3.1. Between-task difference in unassisted condition

Under no assistance, all subjects achieved their task goals (target force production/full extension). Significant between-task differences, however, were found in their muscle coordination and intermuscular coherence.

(1) **Muscle coordination:** The overall muscle activation pattern was significantly affected by the task type ($p = 0.008$). The largest between-task difference was found in the intrinsic muscle activity; the extrinsic muscle activities were not significantly different ($p = 0.264$ for EDC; $p = 0.099$ for FDS), but the FDI activation level was significantly higher during Task 1 ($p = 0.001$; Fig. 3a).

CCR values also indicated a significant between-task difference in the intrinsic muscle activity (Fig. 3b). While the CCR value of the extrinsic-extrinsic muscle pair (EDC-FDS) was not found different between two tasks ($p = 0.441$), those of the extrinsic-intrinsic muscle pairs exhibited significant between-task differences ($p = 0.012$ for FDS-FDI; $p = 0.004$ for EDC-FDI). No significant phase-effect was observed ($p > 0.75$ for all pairs).

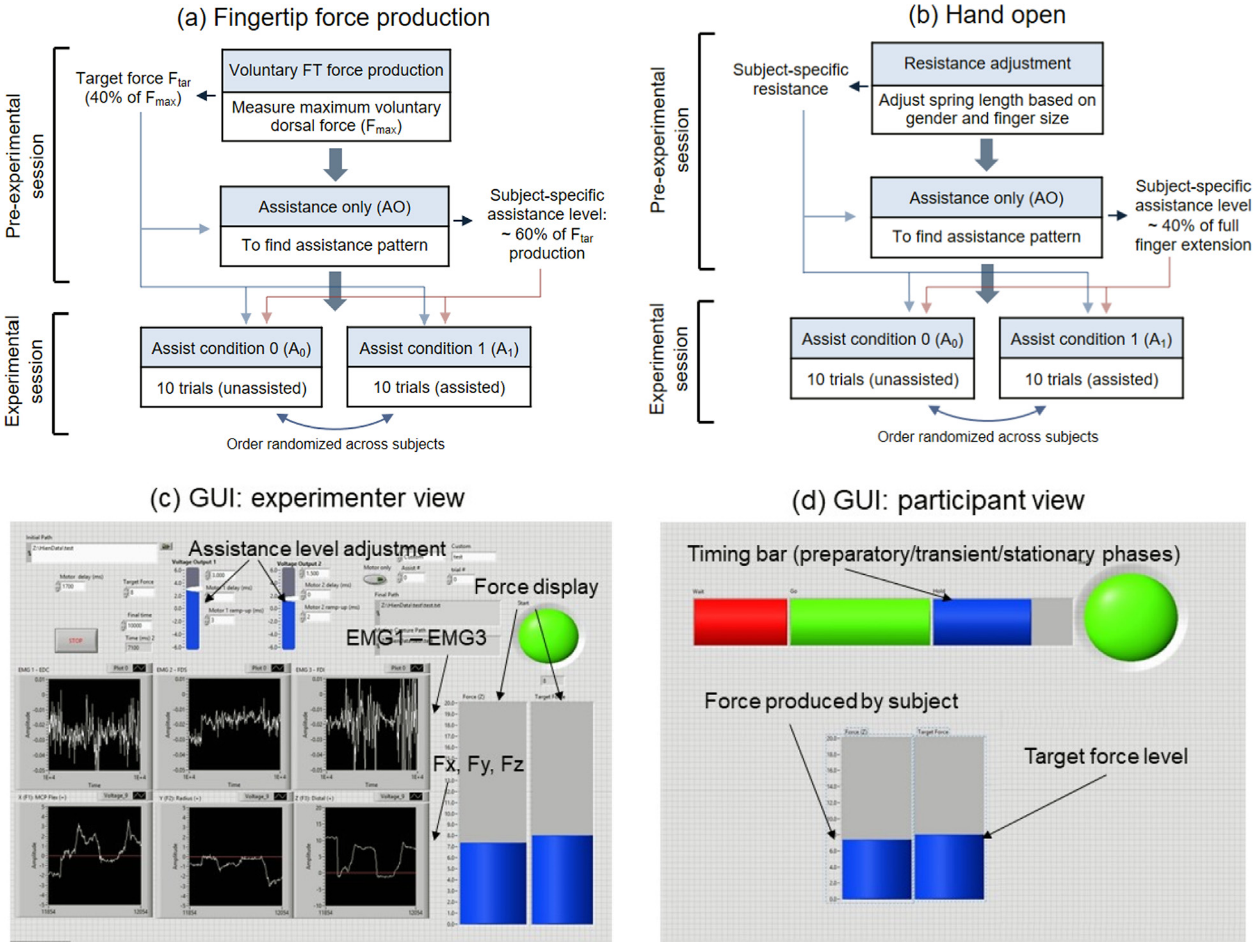


Fig. 2. Experimental setting: (a,b) Experimental protocols for Task 1 (a: isometric); and Task 2 (b: isokinetic); (c) Graphical user interface (GUIs) for user; (d) GUI for experimenter. (a,b) For each task, based on the voluntary task performance, the task 'difficulty' was first adjusted to each subject (Task 1: target force level; Task 2: resistance level). Then, the assistance level appropriate for each subject was found from an iterative process in which the assistance was adjusted based on the task dynamics performed by the device (without subject participation). (c,d) The GUs were used to provide information regarding the timing of the task and task goal (dorsal force magnitude) to the subjects (c), and information of all three forces and EMG signals to the experimenter (d).

(2) **Intermuscular coherence:** The ICI values of all muscle pairs were found significantly greater during Task 1 than during Task 2 (p-values < 0.01 for all pairs). The effects of phase, however, were different between the extrinsic-extrinsic (EDC-FDS) and the extrinsic-intrinsic (FDS-FDI and EDC-FDI) muscle pairs; both phase-effects and phase-task interaction effects were not significant for the extrinsic-extrinsic pair, but found significant for the extrinsic-intrinsic pairs (Table 1). For both extrinsic-intrinsic muscle pairs, the ICI values from Task 1 were significantly smaller during the steady-state phase, while no difference was found during Task 2. These between-task/phase differences were consistently observed in the β-band, while their effects on the α- and γ-bands were less consistent (Table 1).

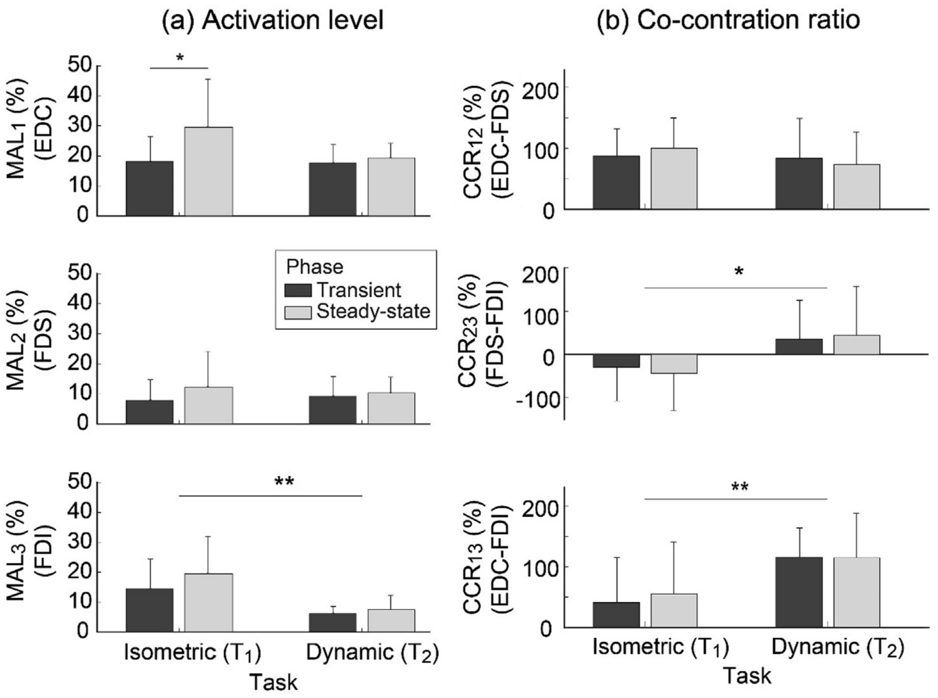
When compared between the muscle pairs, ICI of the extrinsic-extrinsic muscle pair (EDC-FDS) were found significantly greater than those of the extrinsic-intrinsic muscle pairs ($p < 0.01$; Fig. 3c).

3.2. Between-task difference in adaptation to assistance

Two contrasting patterns emerged under the external assistance. The assistance mainly decreased the intrinsic muscle activity during Task 1, while a greater reduction in the extrinsic muscle activities were found during Task 2. Changes in the intermuscular coherence were also different between the tasks (decrease in Task 1 vs. increase in Task 2). The task dynamics were mostly preserved during Task 2, while a significant change was observed in the dynamics during Task 1.

(1) **Muscle coordination:** In both tasks, activation level of all three muscles significantly decreased under assistance ($p < 0.001$ for all intercepts of ΔMALs). But the degree of their change was different between the tasks ($p < 0.001$); reduction in the extrinsic muscle activities (EDC, FDS) was significantly greater in Task 2 (Fig. 4a). The between-task difference was the greatest in the FDS activity ($p < 0.001$), followed by the EDC ($p = 0.073$). Change in the FDI muscle activity was not significantly different ($p = 0.298$).

Changes in the CCR further clarified the pattern of between-task difference in the muscle coordination (Fig. 4b). Under assistance, the extrinsic-extrinsic CCR (ΔCCR_{12}) increased during Task 2, reflecting a significant reduction in the FDS activation, but no such change was observed in Task 1 ($p = 0.016$ for ΔCCR_{12}). In contrast, for the two extrinsic-intrinsic muscle pairs, changes in the CCR val-


(a) Activation level (b) Co-contration ratio

(c) Intermuscular coherence

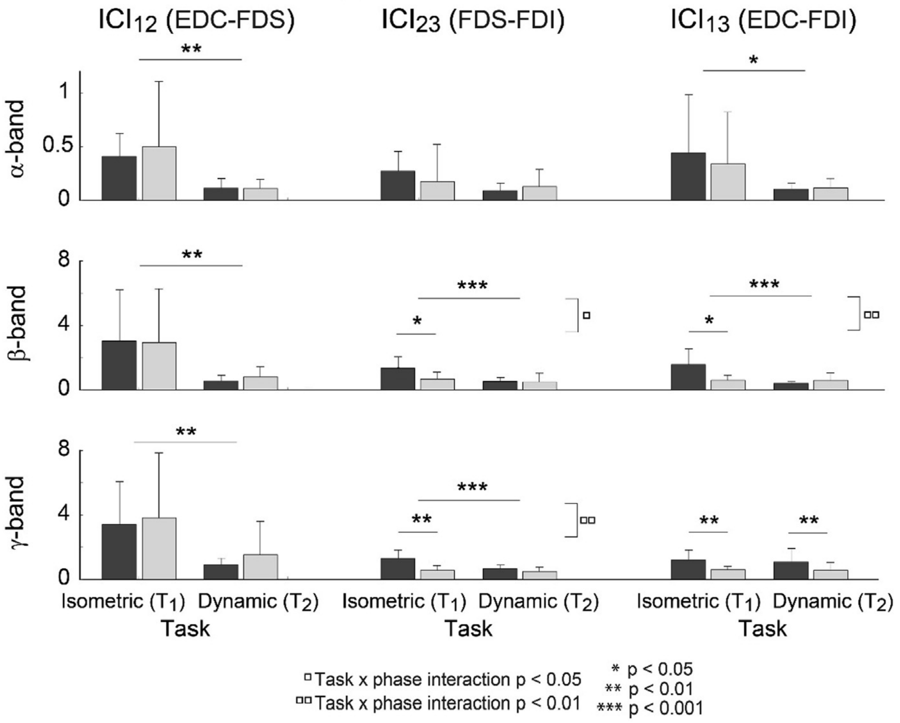


Fig. 3. Between-task difference in (a) muscle activation level (MAL); (b) co-contraction ratio (CCR); and (c) intermuscular coherence integral (ICI). Significant between-task differences were found in the intrinsic muscle activity (a) and CCR of the intrinsic-extrinsic muscle pairs (b). ICI values of Task 1 were found generally larger than Task 2. ICI values of the extrinsic-extrinsic muscle pair were significantly larger than those of the extrinsic-intrinsic muscle pairs. Phase mainly affected extrinsic-intrinsic muscle pairs.

ues (ΔCCR_{23} and ΔCCR_{13}) were significantly greater during Task 1 ($p = 0.001$ for ΔCCR_{23}; $p = 0.015$ for ΔCCR_{13}), reflecting a greater decrease in the FDI activation during Task 1.

(2) **Intermuscular coherence:** Distinct patterns of the changes in the intermuscular coherence (ΔICI) emerged under assistance. In general, the ICI values increased under assistance during Task 2 (increase in the common neural input to the muscles). In contrast, the ICI values decreased during Task 1 (Fig. 4c). Such significant between-task differences were mainly observed in the β-band ($p < 0.01$ for all three pairs) and γ-band ($p < 0.01$ for the two extrinsic-intrinsic pairs), but the ΔICI values in the α-band were not found different between the tasks (Table 2). No significant effect of phase was found in all three pairs (all p-values > 0.302).

(3) **Task performance and biomechanical efficiency:** Under assistance, a significant change in the task dynamics was observed in Task 1. Under assistance, the direction of the fin-

Table 1

p-values for ICI values of the three muscle pairs: (a) EDC-FDS (ICI_{11}); (b) FDS-FDI (ICI_{23}); (c) EDC-FDI (ICI_{13}). Significant task-effects were found in all pairs, while phase-effects were mostly found in the extrinsic-intrinsic muscle pairs (FDS-FDI, EDC-FDI).

Pair	Band	Task	Phase	Task × Phase
EDC-FDS	All	**0.009**	0.785	0.860
	α	**0.001**	0.670	0.630
	β	**0.002**	0.915	0.817
	γ	**0.003**	0.575	0.985
FDS-FDI	All	**0.001**	**0.010**	**0.050**
	α	0.070	0.604	0.383
	β	**<0.001**	**0.020**	**0.021**
	γ	**<0.001**	**<0.001**	**0.009**
EDC-FDI	All	**0.010**	**0.011**	**0.013**
	α	**0.013**	0.683	0.635
	β	**0.001**	**0.016**	**0.002**
	γ	0.403	**0.004**	0.657

Bold indicates statistical significance, $p < 0.05$.

gertip force shifted toward proximal direction (mean ± SD angle: $A_0 = 15.6° \pm 4.3°$; $A_1 = -20.4° \pm 7.9°$; $p < 0.001$; Fig. 4a). This change in the force direction also led to a significant change in the biomechanical efficiency; the total joint moment (M_{tot}) significantly increased from 1.82Nm ± 0.42Nm (no assistance) to 3.52Nm ± 0.61Nm (under assistance) ($p < 0.001$), indicating a significant decrease in the biomechanical efficiency.

However, no significant changes were observed during Task 2. Temporal difference between the peak-velocity times of the MCP and PIP joints (ΔT_{pv}) was not found significantly different between conditions (0.04 s ± 0.61 s without assistance; 0.23 s ± 0.65 s under assistance; $p = 0.35$). Similarly, correlation coefficients between MCP and PIP joint angular profiles (r-values), which quantified spatiotemporal interjoint coordination, were not significantly different (0.94 ± 0.03 without assistance; 0.92 ± 0.05 under assistance; $p = 0.37$).

4. Discussion

A significant between-task difference was observed in the muscle coordination during unassisted condition, which supports our first hypothesis on the task effect (significant task-effect on the coordination of the hand muscles). The change in the muscle coordination patterns under assistance also differ significantly between the two tasks, supporting our second hypothesis on the task effect (significant task effect on the motor adaptation to assistance).

4.1. Task dynamics affect muscle coordination patterns

During unassisted performance, the largest between-task difference was found in the FDI activity. While the intrinsic hand muscles were found to actively participate in isometric tasks such as precision manipulation (Balasubramanian and Matsuoka, 2009) and dorsal fingertip force production (Maier and Hepp-Reymond, 1995), their functional role in (extension) movements is less straightforward, since their excursion produces distal joint extension (DIP/PIP) but proximal joint *flexion* (MCP) (An et al., 1983). Intrinsic muscle activities do not correlate well with angular displacements during finger extensions (Long and Brown, 1964); such biomechanical *ambiguity* could also explain high between-subject variability in their activities during finger extension (Darling and Cole, 1990).

The observed between-task differences in the FDI activity may also be due to their physiological characteristics; interosseous muscles have relatively large CSA with low fiber length/muscle length ratio, making them suitable for static force production with low excursion (Jacobson et al., 1992). Their short excursion may also explain their inconsistent activation during movements (Long and Brown, 1964).

4.2. Task dynamics affect adaptation to assistance

We also found that the task dynamics significantly affect the motor adaptation to a targeted muscle assistance. During Task 1, assistance led to a greater decrease in the intrinsic muscle activity (FDI), which affected the extrinsic-intrinsic muscle coordination. This also led to a reduction in the biomechanical efficiency (increased joint moments), which does not meet the optimality criteria reported in previous studies (e.g., An et al., 1985). In contrast, changes in the muscle coordination under assistance was much smaller during movements, and the task dynamics (i.e., spatiotemporal joint coordination) were maintained under assistance.

Several physiological mechanisms could have contributed to the between-task difference. The functional importance of the intrinsic hand muscles in force production, due to their physiological characteristics (large CSA/short excursion), could also explain its higher sensitivity to assistance (significant reduction under assistance). Conversely, the extrinsic muscles still needed to be activated to maintain structural stability. Furthermore, while the ‘function’ of the intrinsic muscle in Task 1 (dorsal force) can be substituted by the assistance, its function in Task 2 cannot be replaced by the assistance since the action of the intrinsic and extrinsic muscles are distinctly different; both muscles need to be activated simultaneously to extend all joints.

Additionally, task dynamics could have affected the amount of information delivered by sensory afferents; this explains why task performance was altered/degraded in Task 1, but not in Task 2. Many sensory afferents of human fingers are sensitive to the change in stimulus (angle/position), but they do not encode absolute joint position/angle (Proske and Gandevia, 2012). Joint angle can be indirectly estimated by muscle spindles that decode muscle length, but this is often subject to error. Joint receptors are also sensitive to changes in joint angles, while joint positions/angles are encoded only at near-end of the range of motion (Burke et al., 1988). Similarly, skin receptors mainly contribute to movement sensations. Therefore, more sensory information was available to subjects regarding the movements during Task 2, which could have helped them maintain task dynamics.

Our postulation regarding the sensory information is supported by the coherence analysis, which is often used to quantify neural drive to hand muscles (e.g., Kilner et al., 1999; Poston et al., 2010; Lee et al., 2014b). Previous studies showed that inputs from somatosensory receptors enhance the coordination of the hand

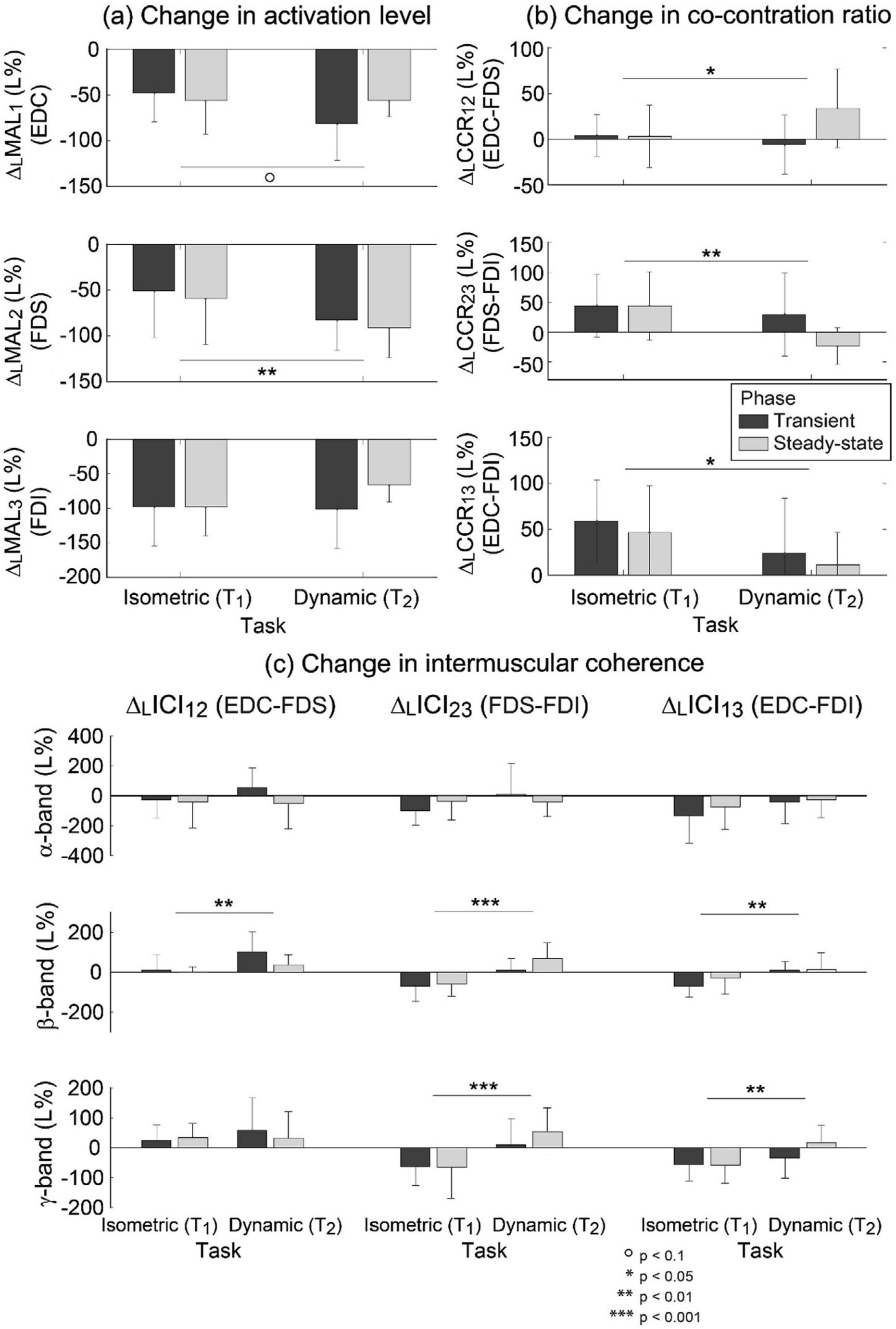


Fig. 4. Change in (a) muscle activation level (MAL); (b) co-contraction ratio (CCR); and (c) intermuscular coherence integral (ICI) under assistance. Significant between-task differences were found in the extrinsic muscle activities (a) and CCR values of all muscle pairs (b). ICI values of Task 1 were found to generally decrease under assistance, while those of Task 2 remain unchanged or increased (c).

muscles, while absence of sensory information could significantly reduce intermuscular coherence (nerve anaesthesia; Fisher et al., 2002; deafferentiation; Kilner et al., 2004), suggesting that intermuscular coherence can gauge neural synchrony mediated by peripheral feedback. Note that, in our study, the coherence values significantly decreased under assistance during Task 1 but increased during Task 2. It is possible that, under external assistance, coordination of the hand muscles was enhanced via somatosensory feedback in Task 2, which also helped subjects maintain movement patterns. On the contrary, in the absence of necessary peripheral information (Task 1), both the task performance (fingertip force direction) was altered and its efficiency (total joint moment) were degraded.

4.3. Implications

Our findings suggest that the task type should be carefully selected for assisted neuromotor trainings, as it could affect motor adaptations. Typically, assistance is required for the training of individuals with upper/lower motor neuron diseases due to their physical impairment. In such cases, the task type should be selected based on the impairment patterns of individual patients.

Table 2
p-values for Δ_LICI values of the three muscle pairs: (a) EDC-FDS ($\Delta_L ICI_{11}$); (b) FDS-FDI ($\Delta_L ICI_{23}$); (c) EDC-FDI ($\Delta_L ICI_{13}$). Significant task-effects were found mainly in β- and γ-bands.

Pair	Band	Task	Phase	Task × Phase
EDC-FDS	All	**0.041**	0.302	0.665
	α	0.206	0.269	0.626
	β	**0.007**	0.120	0.240
	γ	0.003	0.819	0.701
FDS-FDI	All	**<0.001**	0.488	0.213
	α	0.072	0.787	0.211
	β	**<0.001**	0.126	0.511
	γ	**<0.001**	0.439	0.146
EDC-FDI	All	**0.003**	0.550	0.441
	α	0.076	0.411	0.717
	β	**0.001**	0.264	0.567
	γ	**0.006**	0.260	0.238

For instance, many stroke patients exhibit weakness in their extrinsic finger extensors (Kamper et al., 2006); an ‘assisted’ isometric finger extension could be prescribed to these patients, as it could emphasize the contribution from EDC muscle (see Lee et al., 2018). Conversely, for others with intrinsic muscle impairments (e.g., peripheral neuropathy; Stewart, 1987), they would benefit from an ‘unassisted’ isometric extension task as it could promote the use of the intrinsic hand muscles. For stroke survivors who experience difficulty in properly coordinating their intrinsic and extrinsic hand muscles (Lee et al., 2013), movement training with assistance would be preferred since the assistance could promote their coordination – as indicated by the intermuscular coherence values – while helping them complete the task.

4.4. Limitations of the study

The EMG signals were recorded only from three muscles. It is possible that other intrinsic muscles such as palmar interosseous or lumbrical muscles may have exhibited different activation patterns. However, intrinsic hand muscles generally activate in a similar way during finger extension (Long and Brown, 1964), which is also necessary to maintain the lateral (radial/ulnar) stability. Similarly, the FDS muscle activity can represent the activation pattern of both flexor muscles (FDP/FDS), as their activations were found to be coupled during concurrent joint extension in human (Long and Brown, 1964). In a study with primates, the FDS activity was found to be better correlated to finger extension than FDP (Schieber, 1995).

The forearm posture was different between the two tasks (neutral in Task 1; pronated in Task 2; Fig. 1), which could have, in part, contributed to the between-task difference in the muscle coordination. However, previous studies showed that the effects of forearm rotation on the hand muscle coordination become significant only with the wrist joint flexion (Mogk and Keir, 2003); thus we postulate that the effects of the forearm posture were relatively small as the wrist flexion was maintained neutral in our experiments.

Although subjects were asked to perform the task with their index (Task 1) or index/middle fingers (Task 2), it is possible that the other digits were engaged in the task, which could have affected the EMG data. While we attempted to target only the 1st compartment of the extrinsic muscles (EDC, FDS), it is possible that the electrode may have captured the activity of the other compartments, which could have affected the recorded EMG data.

While we attempt to adjust the task conditions to make the agonist activation levels comparable between the tasks, the EDC activation level was generally greater during the isometric task (Task 1), which may have affected the muscle coordination patterns; however, previous studies showed that healthy subjects generally maintain the same muscle coordination patterns across a range of fingertip force magnitudes (Valero-Cuevas, 2000), indicating the small difference in our study would not have led to observed between-task difference in the muscle coordination.

Lastly, the distribution of some outcome variables was skewed (asymmetrical; not normally-distributed), due to the nature of these variables (e.g., ratio of two metrics). Although we performed log-transformation to address the issue, some of these variables remain skewed even after the transformation, possibly due to the relatively small number of subjects examined in this study.

5. Conclusions

In this study, we showed that dynamic characteristics of a manual task significantly affect the coordination between the extrinsic and intrinsic hand muscles, as well as their adaptation to assistance. Coherence analyses showed that isolated modulation of intrinsic hand muscles during isometric task may be due to the neural decoupling between the extrinsic and intrinsic hand muscles induced by assistance, which was not observed during movements. The task type should be carefully selected based on subject-specific motor patterns during assisted neuromotor trainings, as different patterns of motor adaptation can emerge based on the task types under assistance.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Protocol

(1) Task 1 (isometric): Subjects first produced maximum voluntary dorsal fingertip force (MVF), which determined their target force F_{tar} (40% of the MVF). Under assistance-only condition (AO), while subjects maintained the finger posture, the exotendon was pulled to produce fingertip forces. The assistance level for each subject was then determined as the level producing about 60% of F_{tar}.

Two assistance conditions (A_0: unassisted; A_1: assisted) were then tested. In A_0, subjects performed the task without assistance. In A_1, subjects were instructed to “exert the force with the help of the device” while the device provided assistance at the assistance level determined under AO (feedforward control). The custom GUI provided visual cues regarding the fingertip force magnitude and the timing with a sliding bar with marks (force development phase: 3-sec; force maintenance phase: 3-sec). The assistance was linearly increased to this pre-determined assistance level during the force development phase (between 0-sec and 3-sec) in order to prevent any reflexive response due to a sudden change in the external force.

(2) Task 2 (isokinetic): For each subject, resistance provided by the flexor exotendon (ET_{FDP}) was adjusted based on the finger segment length and gender. We adjust the attachment point of the spring so that the cable connected to the spring remained taut (without deformation of the spring) in the fully flexed posture of each subject. Springs with different stiffness values were used so that the activation level of the EDC muscle during movements was approximately 20% to 30% of their maximal level. The assistance level was then determined under AO; the assistance level was determined as the force to achieve about 40% of the full finger extension.

Two assistance conditions (A_0/A_1) were then tested. Subjects performed 'timed' finger extension movements, consisting of movement (3-s) and posture maintenance (3-s) phases. Similar to Tsk 1, the assistance level was increased to the predetermined assistance level during the movement phase. The GUI provided visual cues regarding the timing with a sliding bar with marks.

Appendix B. Data analysis

Activation level and co-contraction ratio were computed from the rectified/low-pass-filtered (5 Hz) EMG data, and intermuscular coherence from raw EMG data. Task dynamics were quantified from the load cell and motion capture data.

(1) **Mean Activation Level (MAL)**: MALs of the three muscles (MAL_i; $i = 1$: EDC, 2: FDS, 3: FDI) were estimated by averaging the normalized EMG profiles during each phase (transient: 0–3 s; steady-state: 3–6 s).

(2) **Co-contraction ratio (CCR)**: CCR of the three muscle pairs, EDC-FDS (CCR_{12}), FDS-FDI (CCR_{23}), and EDC-FDI (CCR_{13}) were estimated from their activation profiles: a regression slope of the two activation profiles (dynamic phase), or the ratio between the mean muscle activation levels (steady-state phase). For the dynamic phase, given the activation profiles of two muscles during movements (from 0 s to 3 s), a least square regression line was obtained by multiplying pseudoinverse of the data matrix of the activation profile of one muscle to that of the other muscle (least-square linear regression). The log transformation was performed to address the skewness of the distribution (Cole, 2000).

$$CCR_{mn} = \ln\frac{MAL_m}{MAL_n} \times 100(L\%)$$

(3) **Intermuscular coherence integral (ICI)**: EMG-EMG coherence between muscle-pairs was estimated from concatenated data (per condition/block) using non-overlapping segments with a frequency resolution of 1 Hz, employing a script developed by Neurospec (Halliday et al., 1995). Only the coherence values >95% confidence limit were z-transformed. The integral of z-transformed coherence (ICI) was calculated within the three frequency bands of interest: α (8–12 Hz), β (13–35 Hz) and γ (36–55 Hz). Similar to the CCR values, the log transformation was performed on the ICI values.

(4) **Change in MAL, CCR, ICI**: For the MAL, CCR, ICI values, and their relative changes under the assistance were computed to account for high between-subject variability. The log change in percent (L%; Δ_L) was used to address asymmetry/non-additivity of the relative measures (Cole, 2000). For instance, the relative change of MAL was computed as:

$$\Delta_L MAL_m = \ln\frac{MAL_m(A_1)}{MAL_m(A_0)} \times 100(L\%)$$

Here, m (muscle) = 1 (EDC), 2 (FDS), 3 (FDI); A_i (assistance) = A_0 (none), A_1 (assisted). $\Delta_L CCR_{mn}$ and $\Delta_L ICI_{mn}$ were computed in the same way (m, n: muscles).

(5) **Task dynamics:** Three different measures were computed for each task:

a. Task 1
  - Task performance: Task error ε_F was computed as the difference between the target and produced forces during the steady-state phase, normalized by F_{tar}.
  - Goal-irrelevant output: The shear (distal/proximal) force represents a motor output in the 'goal-irrelevant' dimension (Todorov and Jordan, 2002). The angular deviation of the force from the normal direction was computed.
  - Biomechanical efficiency: Joint moments required to produce the fingertip force were computed using a Jacobian matrix and the measured force vector, similar to the procedure used in previous studies (Kamper et al., 2006). Briefly, the segment lengths of individual subjects were computed from their height (Lee and Zhang, 2005), then the lengths and the joint angles were used to yield the Jacobian matrix (see Appendix A in Kamper et al., 2006 for the full equation).

b. Task 2
  - Task performance: Total extension angle of the three joints was computed.
  - Goal-irrelevant output: Temporal coordination of the PIP and MCP joints was evaluated by the between-joint difference in times at peak velocity (t_{Vmax}), which represents the goal-irrelevant output, since the goal was defined in the spatial dimension.
  - Biomechanical efficiency: Joint moment profiles required to produce the observed movement patterns were computed.

(6) **Statistical analysis:** A multivariate analysis of variance was then implemented (SPSS; IBM Corp., Armonk, NY). For the task dynamics variables, univariate analyses of variance was used.

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