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**IS SYNERGISTIC ORGANISATION OF MUSCLE COORDINATION ALTERED IN PEOPLE
WITH LATERAL EPICONDYLALGIA? A CASE-CONTROL STUDY**

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ABSTRACT

Background: Lateral epicondylalgia is a common musculoskeletal disorder and is associated with deficits in the motor system including painful grip. This study compared coordination of forearm muscles (muscle synergies) during repeated gripping between individuals with and without lateral epicondylalgia.

Methods: Twelve participants with lateral epicondylalgia and 14 controls performed 15 cyclical repetitions of sub-maximal (20% maximum grip force of asymptomatic arm), pain free dynamic gripping in four arm positions: shoulder neutral with elbow flexed to 90° and shoulder flexed to 90° with elbow extended both with forearm pronated and neutral. Muscle activity was recorded from extensor carpi radialis brevis/longus, extensor digitorum, flexor digitorum superficialis/profundus, and flexor carpi radialis, with intramuscular electrodes. Muscle synergies were extracted using non-negative matrix factorisation.

Findings: Analysis of each position and participant, demonstrated that two muscle synergies accounted for >97% of the variance for both groups. Between-group differences were identified after electromyography patterns of the control group were used to reconstruct the patterns of the lateral epicondylalgia group. A greater variance accounted for was identified for the controls than lateral epicondylalgia ($P=0.009$). This difference might be explained by an additional burst of flexor digitorum superficialis electromyography during grip release in many lateral epicondylalgia participants.

Interpretation: These data provide evidence of some differences in synergistic organisation of activation of forearm muscles between individuals with and without lateral epicondylalgia. Due to study design it is not possible to elucidate whether changes in the coordination of muscle activity during gripping are associated with the cause or effect of lateral epicondylalgia.

Keywords: Tennis elbow; muscle synergies; non-negative matrix factorization; electromyography

Highlights:

- Two muscle synergies are used for gripping by individuals with lateral epicondylalgia and pain-free controls.
- Lateral epicondylalgia is characterised by subtle, but significant, changes in muscle synergies explained by differences in pattern of forearm muscle activation.
- Motor coordination may be relevant for aetiology and rehabilitation of lateral epicondylalgia.

1 INTRODUCTION

Lateral epicondylalgia (LE) is a common musculoskeletal condition, generally considered to affect the extensor carpi radialis brevis (ECRB) portion of the common extensor tendon of the forearm [1, 2]. LE is characterised as a painful impairment of physical activity involving gripping or manipulation of objects within the hand [3, 4] and impacts substantially on participation in occupation [5] and recreation [6]. Although coordination of muscle activity for gripping is thought to be relevant for provocation and persistence of LE [7], only two studies have considered differences in muscle coordination during gripping [8, 9].

Gripping biomechanics are complex, requiring fine coordination of the forearm muscles [7]. This is because the finger flexor muscles, that generate the force of gripping, cross multiple joints and their actions at the wrist must be opposed to maintain wrist position [7]. Although this could be achieved by activation of the ECRB, extensor carpi radialis longus (ECRL) and extensor carpi ulnaris muscles, that do not cross the finger joints, the coordination is complicated by muscle redundancy with many more muscles available (degrees of freedom) than are required [10]. To resolve this complexity, activation of groups of muscle in synchrony (referred to as muscle synergies or motor modules) has been suggested to represent “building blocks” to reduce the degrees of freedom to control [11-13]. For example, five muscle synergies have been identified during gait; each explaining functional subtasks [14, 15].

LE involves four features of abnormal motor control that might reflect changes in muscle synergies. First, strength of metacarpophalangeal joint extension (extensor digitorum communis (EDC)) is spared despite strength deficits in wrist flexion/extension and metacarpophalangeal joint flexion [8]. Second, participants with LE adopt less wrist extension during gripping than pain-free controls (i.e. closer to the neutral position of the wrist) [16] and this reduces grip strength and results in a greater EDC muscle activity [17]. Third, LE participants use less extensor carpi radialis activation during sustained grip than pain-free controls [8]. Fourth, mapping of the motor cortex has revealed less complex

representation of the wrist extensor muscles (i.e. fewer areas of peak excitability) in LE than controls [18]. This is interpreted to suggest less complex control of muscle coordination. For these reasons we hypothesised that the variance accounted for by the synergies used for gripping would be less in individuals with LE than without. Further, function involves gripping in various upper limb position (e.g. combination of elbow and forearm movements). This alters grip strength [19, 20] and muscle activity [17], and may influence muscle coordination.

The primary aim of this study was to determine whether muscle coordination during repeated gripping (considering both muscle synergies and individual electromyographic [EMG] patterns) differs between people with and without LE, in four different upper limb positions. A second aim was to investigate whether the wrist position during gripping differs between groups.

2 EXPERIMENTAL PROCEDURES

A case-control study design was used to evaluate differences in synergistic patterns between individuals with LE and age- and sex-matched controls who reported no symptoms of LE. To address the primary aim we used a non-negative matrix factorization (NMF) algorithm to identify muscle synergies from intramuscular (fine-wire) EMG recordings of ECRB, ECRL, EDC, flexor carpi radialis (FCR), flexor digitorum superficialis (FDS), and flexor digitorum profundus (FDP). Potential differences in the number of muscle synergies were identified if the synergies extracted from the EMG data accounted for different amounts of variance between groups. Potential differences in the composition of muscle synergies were identified if the synergies extracted for the control group (from the dataset composed of all control subjects) did not accurately reconstruct the EMG patterns of the LE participants.

2.1 Participants

Fifteen participants with clinical signs of LE and 15 with no history of elbow pain or injury (pain-free controls) were recruited. Participants were also involved in another study investigating the relative contribution of forearm muscle activity during an isometric gripping task [9]. That study did not investigate muscle synergies or repeated movements [9]. The

different task and methods in the present study provide a unique set of observations. Participants with LE were included if they had pain over the lateral humeral epicondyle for >6 weeks that was provoked by palpation, resisted wrist and middle finger extension, and gripping activities. Participants were excluded if they had; bilateral symptoms, previous LE, pain during passive range of motion (neck and arm), reproduction of arm pain by neurodynamic tests of the upper limb (indicative of cervical radiculopathy or peripheral nerve involvement), previous treatment (conservative or surgical), or and major neurological/systemic disease. Pain-free controls were included if they had no present or previous lateral elbow pain, full pain-free range of motion (active and passive), and no pain with gripping or resisted wrist extension. Participants were excluded from either group if they had neck or arm pain (other than LE in the LE group), which prevented participation in work or recreation, or required clinical consultation in the past 6 months. Participants were recruited using media advertising. The institutional Medical Research Ethics Committee approved the study and written informed consent was obtained.

2.2 Characterisation of lateral epicondylalgia

Clinical measures including the patient-rated tennis elbow evaluation (PRTEE) form, pain-free grip force, and numerical rating scale (NRS) for pain intensity were recorded to characterise the LE group. The validated PRTEE is specific to LE, measuring pain severity and functional disability with a maximum score of 100 (higher score implies greater pain/disability) [21]. An 11-point NRS (0 = no pain, 10 = worst pain imaginable) assessed worst pain over the preceding week. A digital grip dynamometer (MIE Medical Research Ltd., Leeds, UK) measured pain-free grip force. The participant ceases gripping at the onset of pain [4]. For this task controls maximally gripped the dynamometer as they experienced no pain. Grip force was measured with the participant in supine with elbow extended beside the body and forearm pronated with the palm facing down and the dynamometer handles supported on the table [4, 22]. As a clinical measure of LE, the maximum grip force generated by the LE participants in their affected arm without provoking pain (pain-free grip

force) was less than the maximum pain-free grip force generated by the control participants (-73%; $p < 0.001$). Table 1 presents participant demographics and characteristics.

Table 1 Participant characteristics and demographics (mean (SD) or n (%) or n (range))

	Lateral Epicondylalgia (n = 12)		Healthy Controls (n = 14)	
Sex: Female	8 (66%)		9 (64%)	
Age in years (range)	51.6 (37 to 62)		51.4 (39 to 67)	
Right arm dominant	10 (83%)		13 (93%)	
Dominant arm affected	10 (83%)		n/a	
Dominant arm included in analysis	10 (83%)		10 (71%)	
Symptoms duration in weeks (range)	22.2 (8 to 52)		n/a	
PRTEE (score/100)	37.7 (13.6)		n/a	
NRS (0 - 10)	7.4 (1.8)		n/a	
	LE affected	LE non-affected	Control matched affected	Control matched non-affected
Pain-free grip force in Newtons	81.7 (46.4)*	254.6 (68.9)	298.8 (76.8)	281.2 (71.4)

* $P < 0.05$ for comparison between LE and Control groups; PRTEE – patient rated tennis elbow evaluation, NRS – numerical rating scale, n/a – not applicable

2.3 Study measurements

Grip force during the experimental tasks was recorded using an electronic grip dynamometer (MIE Medical Research Ltd., Leeds, UK; weight - 0.452 kg; span - 4.5 cm for males and 3.5 cm for females). An electrogoniometer (SG65, Biometrics Ltd., Newport, UK) was attached to the dorsal surface of the third metacarpal of the hand and midline of the posterior aspect of the forearm to measure wrist angle. Electrogoniometer and dynamometer data were recorded at 100 Hz using a Power1401 Data Acquisition system and Spike2 software (Cambridge Electronic Design, UK).

Bipolar fine-wire electrodes [two Teflon-coated 75 μm stainless-steel wires with 0.5 mm insulation removed from the tip, bent back at 1.5 and 3 mm to form hooks, and threaded into a hypodermic needle (25G x 25 mm)] were used to record myoelectric activity from ECRB, ECRL, EDC, FCR, FDS, and FDP, bilaterally. Electrode placement used previously

established procedures where available [23, 24], with real-time ultrasound guidance (12 MHz, Logic E, GE Healthcare, Canada) and palpation during activation. Prior to insertion, the skin was cleaned with antiseptic (BD Persist™ Plus, Becton Dickson Infusion Therapy Systems Inc., Utah, USA). One experimenter inserted all electrodes. A ground electrode (3M Red Dot, London) was placed over the lateral epicondyle. EMG data were pre-amplified 10,000 times, band-pass filtered between 20–1000 Hz (Neurolog, Digitimer, UK), and sampled at 2000 Hz with the mechanical data.

2.4 Protocol

Participants sat with their back supported, knees and hips in 90° of flexion and feet on the floor. Participants performed a maximum voluntary grip with the asymptomatic arm for 3-5 s with strong verbal encouragement. The task was repeated in four positions: shoulder in neutral beside the body with the elbow flexed to 90° (proximal third of the ulna resting on the armrest) and forearm either pronated (position 1) or neutral (position 2); and shoulder flexed to 90° with the elbow extended and the forearm either pronated (position 3) or neutral (position 4). These four positions were selected to investigate whether differences in muscle length (elbow flexion and extension) and/or influence of gravity (forearm supported/unsupported) altered muscle synergies. Maximum grip of the asymptomatic arm was used for target calculation (estimate of 20% maximum grip force in the symptomatic arm) such that pain was not provoked in the symptomatic arm prior to testing. Tasks were performed with the order of the four arm positions randomised and two minutes rest between maximal contractions in each position. The 20% target was selected as it was pain-free for participants with LE. No participant reported pain during the gripping task and all participants reached the predetermined grip force of 20% MVC in the allotted timeframe in all limb positions. The experimental task involved 15 consecutive submaximal, pain-free repetitions (0.5 Hz) of a dynamic gripping task between 0 to 20% of the maximum grip strength in each position with 1-min rest between positions. Visual feedback of the force target was provided on a computer screen and participants practiced the task with each arm for up to 15 repetitions for familiarisation.

2.5 Data management

2.5.1 EMG data

Raw EMG data were visually inspected for artefacts and 8 to 12 consecutive repetitions were retained for analysis. Data for 3 LE and 1 control participant(s) could not be included as the EMG signal for one or more muscles was too selective and represented only a few motor units or included substantial movement artefact that precluded accurate analysis. For controls, EMG analysis (including calculation of individual EMG patterns and extraction of synergies) was completed on the side with the best EMG signals (i.e. highest signal-to-noise ratio and minimization of movement artefacts). This resulted in the selection of 10 dominant and 4 non-dominant arms. We also compared muscle coordination between sides for both controls and LE participants. Because of the selection of the EMG signals based on the criteria mentioned above, this between-sides comparison was performed on 11 controls and 8 LE participants.

EMG data were band-pass filtered (20-950 Hz, Butterworth filter, 2nd order), rectified, smoothed with a zero-lag low-pass filter (3 Hz, Butterworth filter, 2nd order), and time-normalized to 200 data points for each gripping repetition. EMG amplitude for each muscle was normalized to the average of its peak amplitude for all repetitions.

2.5.2 Wrist angle and grip force data

Wrist angle (flexion and extension) and grip force signals were analysed for the same repetitions as the EMG signal. Data were low-pass filtered (3 Hz; Butterworth filter, 2nd order) and averaged to obtain a single mean value for wrist position in each of the four task positions.

2.5.3 Extraction of muscle synergies

Non-negative matrix factorization was performed on the pre-processed EMG dataset. We implemented the Lee and Seung [25] algorithm as further described in previous works [15, 26, 27]. The algorithm was repeated 20 times. The lowest cost solution was retained (i.e., minimized squared error between original and reconstructed EMG patterns).

First, muscle synergies were extracted for each participant from an EMG matrix merging the 4 gripping positions. We iterated the analysis by varying the number of synergies between 1 and 6 (i.e. number of recorded muscles) and selected the least number of synergies that accounted for >90% of Variance Accounted For (VAF) or until adding an additional synergy did not increase VAF by > 5% [26]. Mean total VAF was calculated as described in [28]. Then, by using the same technique, muscle synergies were extracted for each participant and gripping position independently.

2.5.4 Between-group and between-side similarity

To assess the similarity/difference of the muscle synergies between controls and LE participants, we checked that the muscle synergies extracted from the control population accounted for the EMG patterns of each of the controls and LE participants. To do this, the muscle synergy vectors matrix (W_{control}) extracted from the entire control population (dataset composed of all control subjects) was held fixed in the NMF algorithm while the activation coefficient matrix of the compared subject (C_{subject}) was free to vary [28, 29]. C_{subject} was initialized with random values and iteratively updated until convergence (see van den Hoorn et al. 2014 for more details [15]). This process was performed for each task separately. Note that when the compared subject was a control participant, they were not taken into account in the calculation of the synergy vector matrix for the control population, i.e., the initial matrix was composed by 13 (14-1) control participants. Twenty-six pairwise comparisons (14 for controls and 12 for LE participants) were performed.

We also compared the synergies between sides using a similar cross-validation procedure applied on each participant separately and on all tasks merged within the same matrix. The “non-affected” side was considered as the left side for controls. Note that similar results are obtained if the “non-affected” side is defined as the opposite side.

The overall VAF were used to quantify the success of the fixed muscle weightings and the newly computed synergy activation coefficients to reconstruct the initial EMG patterns.

2.6 Statistical analysis

VAF data for the primary outcome of between-group differences passed the Shapiro-Wilk normality test, however VAF data for the between-side comparison did not. Log-transformation was applied to the VAF data for between-side comparison. Statistical analyses were performed using Statistica Software (StatSoft Inc, Oklahoma, USA). A repeated measures ANOVA (between-subjects factor: group [LE vs. control]; within-subject factors: elbow position [flexed vs. extended] and forearm position [pronated vs neutral]), was used to compare the VAF values. Forearm and elbow positions were separated to allow comparisons between positions. Separate ANOVA's were used to compare wrist angle and grip force data between groups. Post-hoc analysis was completed using Duncan's multiple range tests. Student's t-tests compared VAF (when muscle synergies were extracted from the merged 4 positions), and grip strength, between groups. Significance was set at $P < 0.05$. Data are reported as mean (standard deviation).

3 RESULTS

3.1 EMG patterns

Figure 1 depicts the ensemble-averaged normalized EMG patterns for the 6 muscles. Although the shape of the EMG patterns was similar between groups for most muscles, differences are noteworthy for FDS. A second, late burst of FDS EMG was observed during the release phase in the LE participants. Inspection of the individual data revealed the burst was present in 7 of the 12 LE participants and 4 of the 14 controls.

3.2 Muscle synergies

Muscle synergies were first extracted for each participant from the 4 positions merged within the same matrix, using the criterion previously described (i.e. VAF >90% or until adding an additional synergy did not increase VAF by >5%), two synergies were identified. These two synergies represented a squeeze and release phase of the cycle, respectively, and accounted for similar VAF in both groups (93.1 (2.6)% and 94.6 (1.7)% for the LE group and pain-free controls, respectively; $P=0.14$).

We extracted and compared synergies for each position separately, 2 synergies accounted for 98.3 (1.3)%, 98.1 (1.0)%, 98.4 (0.8)%, and 98.1 (1.0)% for positions 1, to 4, respectively, for the control participants. When considering the LE participants, 2 synergies accounted for 98.5 (0.5)%, 97.6 (1.6)%, 98.1 (1.0)%, and 97.8 (1.1)% for positions 1, to 4, respectively. There were no between-group differences (Main effect: Group $P=0.52$). Synergy #1 mainly involves ECRB, ECRL and FDP and is activated during the squeeze phase of the grip cycle. Synergy #2 mainly involves EDC and FCR and is activated during the release phase of the grip cycle (Figure. 2).

The similarity of the muscle synergies between sides was assessed using the muscle synergy vectors extracted from the control side to reconstruct the EMG patterns of the contralateral side. The synergy of the “non-affected” side explained 83.3(4.9)% and 86.1(6.4)% of VAF for control group and LE group, respectively. This was not different between groups ($P=0.31$) meaning that the synergies were not more different between sides in LE participants than they were in controls.

The similarity of the muscle synergies between groups was assessed using the muscle synergy vectors extracted from controls (from a dataset merging all the control participants) to reconstruct the EMG patterns of each LE and control participant for each position separately. The synergies of the control group explained between 89.7 (4.3)% and 91.3 (4.0)% of VAF (depending on the position) for pain-free controls and between 83.3 (6.8)% and 89.2 (5.3)% of VAF (depending on the position) for LE participants (Table 2). The VAF values were lower for the LE participants than controls, regardless of the elbow and/or forearm position (Main effect: Group, $p=0.009$). Regardless of group, the VAF values were higher with the forearm in a pronated position (Main Effect: Forearm position $P=0.004$). When the cross validation was undertaken using the muscle synergy vectors extracted from the LE participants to reconstruct the EMG for both groups, there is no difference in the VAF values between the group (Main effect: Group, $P=0.23$). This is best explained by variation between participants in the LE group, such that the synergy vectors of the LE group were less accurate for reconstruction of data for individuals in either group. It is important to note

that although the VAF was lower than for controls, VAF values of the LE group remained high (>83.2%, Table 2). This signifies that the reconstruction of EMG patterns with synergies of controls was not greatly affected by this process.

Inspection of individual data reveals that 5 out of the 12 LE participants (participant number 1, 2, 4, 7 and 10) exhibited a VAF value <80% for at least one position (Table 2). Only 1 out of the 14 pain-free controls (participant number 2) had a VAF value less than this threshold which is based on the work of other authors to select synergies [14] (Table 2). This observation indicates that the synergies of these participants are less similar than the ensemble synergies of the control group. Inspection of the individual EMG patterns of these participants revealed that this lower similarity was mainly explained by the later burst of FDS EMG during the release phase. In some participants the main EMG burst of FDS muscle activity was located at the end of the gripping cycle rather than during (an example of this is shown in Figure 3). As a consequence, the representation of the FDS muscle within Synergy 1 was lower in these participants than the remaining LE participants and controls.

Table 2 Individual VAF (%) from control synergy for separate positions

Participant number	Lateral epicondylalgia				Pain-free controls			
	Position	Position	Position	Position	Position	Position	Position	Position
	1	2	3	4	1	2	3	4
1	82.5	95.3	82.5	78.6	94.0	88.6	93.8	93.4
2	86.4	78.4	88.0	77.4	86.8	80.8	83.8	77.7
3	89.6	86.4	95.0	92.5	90.4	84.2	93.0	88.7
4	89.1	78.5	85.5	74.8	86.1	88.2	85.1	84.7
5	87.2	80.2	85.3	82.6	81.1	89.1	87.2	85.5
6	80.1	86.9	95.7	81.8	90.7	89.9	90.6	91.4
7	86.5	75.4	85.4	73.9	95.9	96.6	97.0	95.3
8	88.2	95.4	95.6	94.6	92.7	91.9	92.1	90.4
9	87.2	85.3	91.5	80.8	88.3	90.5	96.3	92.4
10	74.4	77.2	81.6	83.5	94.1	95.0	90.1	95.4
11	89.7	85.8	89.7	90.3	94.6	93.6	89.4	86.8
12	97.3	91.3	95.2	88.1	92.1	91.0	92.1	94.1
13	-	-	-	-	94.4	84.8	91.0	94.2
14	-	-	-	-	94.7	91.7	96.0	92.7
Mean	86.5	84.7	89.3	83.2	91.1	89.7	91.3	90.2
SD	5.6	6.9	5.3	7.0	4.2	4.3	4.0	5.0

VAF – variance accounted for, SD – standard deviation, bold text highlights those with VAF less than 80% Position 1 – shoulder neutral (0°), elbow flexed (90°), forearm pronated; Position 2 – shoulder neutral (0°), elbow flexed (90°), forearm neutral; Position 3 – shoulder flexed (90°), elbow extended (0°), forearm pronated; Position 4 – shoulder flexed (90°), elbow extended (0°), forearm neutral.

3.3 Grip force and wrist angle

Grip force and wrist angle are presented in Table 3. When comparing 20% MVC, estimated from the non-affected limb of the LE group the repeated measure ANOVA revealed neither a significant main effect for group ($P=0.67$) nor a significant interaction involving group (all $P>0.22$). This indicates that grip force during the pain-free dynamic gripping task was not different between groups, regardless of elbow or forearm position. For both groups a greater grip force was recorded when the elbow was extended than flexed (Main effect: elbow position, $p=0.046$) and when the forearm was neutral compared to pronated (Main effect: forearm position, $p<0.0001$).

The wrist angle during the gripping task did not differ significantly between groups (Main effect: Group $p=0.85$, Table 3), regardless of elbow or forearm position (Interactions: all $P>0.28$). Regardless of group participants gripped with less wrist extension when the forearm was pronated and the elbow flexed than all other positions (Post hoc, all $P<0.03$). Participants gripped with less wrist extension with the forearm pronated and the elbow extended than with the forearm neutral (either elbow flexed ($P<0.001$) or extended ($P<0.001$)).

Table 3 Mean (SD or 95% CI) for grip force and wrist angle during gripping task

	Task position	Lateral epicondylalgia	Pain-free controls	MD (95% CI)
Grip Force (N)	1	52.6 (14.9)	55.1 (12.7)	-2.5 (-13.7 to 8.7)
	2	58.0 (18.4)	59.0 (15.3)	-1.0 (-14.6 to 12.6)
	3	53.0 (16.3)	57.1 (15.7)	-4.1 (-17.1 to 8.8)
	4	58.7 (18.4)	61.5 (15.5)	-2.8 (-16.5 to 11.0)
Wrist Angle (°)	1	18.1 (11.0)	16.3 (11.3)	-1.8 (-10.8 to 7.3)
	2	35.5 (10.3)	33.1 (12.8)	-2.4 (-11.9 to 7.1)
	3	20.2 (11.0)	21.0 (12.0)	0.8 (-8.5 to 10.2)
	4	32.3 (8.8)	32.9 (10.0)	0.6 (-7.1 to 8.3)

MD – Mean difference, 95% CI – 95 percent confidence interval Position 1 – shoulder neutral (0°), elbow flexed (90°), forearm pronated; Position 2 – shoulder neutral (0°), elbow flexed (90°), forearm neutral; Position 3 – shoulder flexed (90°), elbow extended (0°), forearm pronated; Position 4 – shoulder flexed (90°), elbow extended (0°), forearm neutral.

4 DISCUSSION

The primary aim of this study was to determine whether coordination (as quantified by muscle synergies) of forearm muscles during sub-maximal, pain-free dynamic gripping differs between people with LE and pain-free controls. Considering the whole group, data show that the number of muscle synergies was not different between groups. Consistent with our hypothesis the cross validation procedure showed significant differences in VAF between groups, although muscle synergies differed little in each of the elbow or forearm positions. However, individual variation was apparent with some participants (mostly with LE) using an altered activation of FDS. In this study of twenty-six participants, wrist position during gripping did not differ significantly between groups.

4.1 Muscle coordination

The complexity of motor control is thought to be reflected by the number of muscle synergies [30]. In the present experiment, we identified two muscle synergies for both groups. This can be grossly interpreted to suggest a similar complexity of motor control. For both groups the two muscle synergies related to separate gripping phases (i.e squeeze and release for Synergy 1 and 2, respectively). Studies on gripping performed in healthy controls have shown activation of wrist extensor muscles (ECRB, ECRL, EDC, and extensor carpi ulnaris (ECU)) to counteract the flexion moment caused by finger flexor muscles (FDP/FDS) [7, 17, 31]. These data are consistent with Synergy 1 in the current study, which included activation of ECRB, ECRL in conjunction with FDS and FDP. Although EDC generates a wrist extension moment, and is often activated during function to contribute to this role, its tendons also cross the finger joints [7, 31] and its primary role is extension of the fingers [32]. Activation during the release phase of gripping can be explained by this role [31]. During the release phase of gripping co-activation of the wrist flexor muscles (e.g. FCR)

might be required to oppose the wrist extension moment created by the activity of EDC as it opens the fingers. Additionally, the activation of FCR during the release phase of the task is thought to help stabilise the carpal bones, particularly the scaphoid, during movements of the wrist [33]. In our study FCR is less represented within synergy 2 with the elbow extended and the forearm pronated, which might be due to muscle lengthening in this position.

When considering the whole group, our cross-validation analysis showed that synergies used by the LE participants during gripping were different to those of controls, although the VAF (an indicator of the accuracy of the reconstruction of the EMG patterns using the synergy vectors of control participants) remained high (>83.3%). A threshold of VAF 80% has been used as a criterion to select the number of muscle synergies in some studies [14, 15], and was considered here as an indication of acceptable reconstruction accuracy. Despite the reasonable reconstruction for the group as a whole, inspection of individual data revealed that VAF dropped below 80% for one or two positions in nearly half (5 of the 12) of the LE participants but only one (1 of the 14) of the pain-free controls. This observation paralleled the observation of an additional burst of FDS EMG during the release phase in 7 out of 12 of the LE participants and 4 out of 14 of the controls.

Although the present study does not enable more detailed interpretation of the mechanisms or consequence of this difference in coordination, it is possible to speculate the possible relevance for LE in conjunction with other data. Although the present analysis of muscle synergies does not permit comparison of EMG amplitudes, other work, including analysis that includes some participants included in the present study, has shown less activation/contribution of ECRB [8, 9] and greater contribution of EDC and FDP during gripping in people with LE than controls [9]. Although this solution might reduce stress on ECRB, it would be somewhat counterproductive for gripping as EDC activation would oppose the role of FDP in gripping. Taken together, the present synergy data imply that the basic structure of the pattern is maintained, perhaps with modified relative contributions of the individual muscles to force. The additional burst of FDS activation during release in some

individuals might reflect an adaptation to eccentrically control opening of the fingers, as may be necessary as a secondary to greater activation of the EDC muscle.

It is not possible to determine whether the identified difference in muscle synergy in some participants with LE was pre-existing or developed after LE symptoms. In other conditions such as patellofemoral pain, changes in motor control and muscle imbalances have been suggested to precede and potentially contribute to the development of pain and/or injury [34], whereas other motor control strategies develop after pain/injury (e.g. antalgic gait after acute ankle sprain). Most contemporary models propose that changes in muscle coordination in pain act to protect a painful tissue from further pain/injury [35, 36]. This is thought to occur in a manner that varies between individuals [36] which concurs with our data, and that of other EMG studies using experimental pain models [37]. Although the task in the present study was pain-free, participants with LE may have developed specific patterns of motor activity with repeated exposure to pain [3]. As highlighted above, the modified finger flexor muscle activation may be a secondary strategy to unload ECRB during gripping. Another prediction of contemporary theories of motor adaptation to pain is that changes might be detrimental in the long term [36]. An issue worthy of consideration in further studies is whether the modification of coordination of FDS activation has detrimental consequences as a result of additional load on the extensor muscles and interposed joints.

4.2 Wrist position during grip

Although differences in muscle coordination could affect wrist kinematics, the present study found no changes in wrist angle. This is inconsistent with previous data showing less wrist extension (i.e. closer to neutral) during isometric pain-free grip in people with LE than controls [16]. There are five possible explanations for the differences in results. First, the speed/repetitive nature of the task (i.e. 10 – 15 rapid isometric grips vs. one static isometric grip) might alter the kinematics of the task. Second, participants gripped to the first onset of pain (average of 54% MVC) in the earlier study [16], which is substantially greater than the 20% MVC used here. Thus either the intensity or presence of pain could explain the difference. Third, the studies used different methods to measure wrist position

(electrogoniometer attached to the dorsum of the hand and forearm vs. angles between markers placed over the lateral epicondyle, radial styloid process and the head of the fifth metacarpal from photographs [16]). Fourth, the current study investigated multiple upper limb positions compared to the one position of Bisset, Russell [16] (i.e. shoulder flexed to 90°, the elbow extended and forearm pronated). This is unlikely to explain differences between studies as the position used by Bisset, Russell [16] was similar to position 3 used here. Fifth, the previous study used a larger sample and may have had a greater power to detect a difference.

4.3 Methodological considerations

Several methodological issues require consideration. First, although the hypothesis that the central nervous system controls movement through a simplified combination of muscle synergies is supported by experimental [13] and simulation data [38], others data have been interpreted to suggest muscle synergies simply reflect the underlying task constraints [39]. Irrespective of whether muscle synergies reflect “units of control” or “task constraints”, they offer a unique opportunity to analyse the underlying structure of muscle coordination [40]. Second, our analysis does not consider the difference in EMG amplitude (i.e. magnitude of muscle activation). As timing and amplitude of muscle activation have been suggested to be controlled independently [41, 42], differences in EMG amplitude cannot be excluded. Although worthy of consideration, comparison of EMG amplitude between populations requires normalization of EMG amplitude and this brings with it inherent complexities in pain populations because the presence/and or the fear of pain can reduce maximal voluntary activation [43-45]. Third, although the current study benefits from use of fine wire EMG, which minimizes the likelihood of cross talk between myoelectric activity from adjacent muscles [46], and is unique for the field of LE research, the small recording area of these electrodes might not represent the activity of the entire muscles. Fourth, the inclusion of both dominant and non-dominant arms in both groups within the analysis may have impacted on the results as muscle coordination has been shown to differ in some respects between dominant and non-dominant limb [47]. Fifth, although the inclusion

of four different arm positions to investigate the influence of gravity and muscle lengthening on muscle synergies is explorative, the use of an arm rest in the positions of elbow flexion might limit the interpretation of our findings. It is likely that proximal muscles that cross the elbow joint (e.g. biceps brachii, triceps brachii) would be more active in tasks without the support of the arm rest and changes in the length tension properties (e.g. shortened long head of biceps with elbow flexion, internal rotation) will also impact muscle activation.

4.4 Conclusion

In conclusion, this study provides evidence of some differences in synergistic organisation of activation of forearm muscles between people with LE and controls. This was reflected by a specific change in forearm muscle activation during grip release in almost half of the LE participants. Further investigation is required to determine the mechanism and possible consequences of this adaptation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Figures

Figure 1. Ensemble-averaged EMG patterns for each group and each position (Dotted line – LE group, Solid line – pain-free control group). ECRB – extensor carpi radialis brevis, ECRL – extensor carpi radialis longus, EDC – extensor digitorum communis, FCR – flexor carpi radialis, FDS – flexor digitorum superficialis, FDP – flexor digitorum profundus

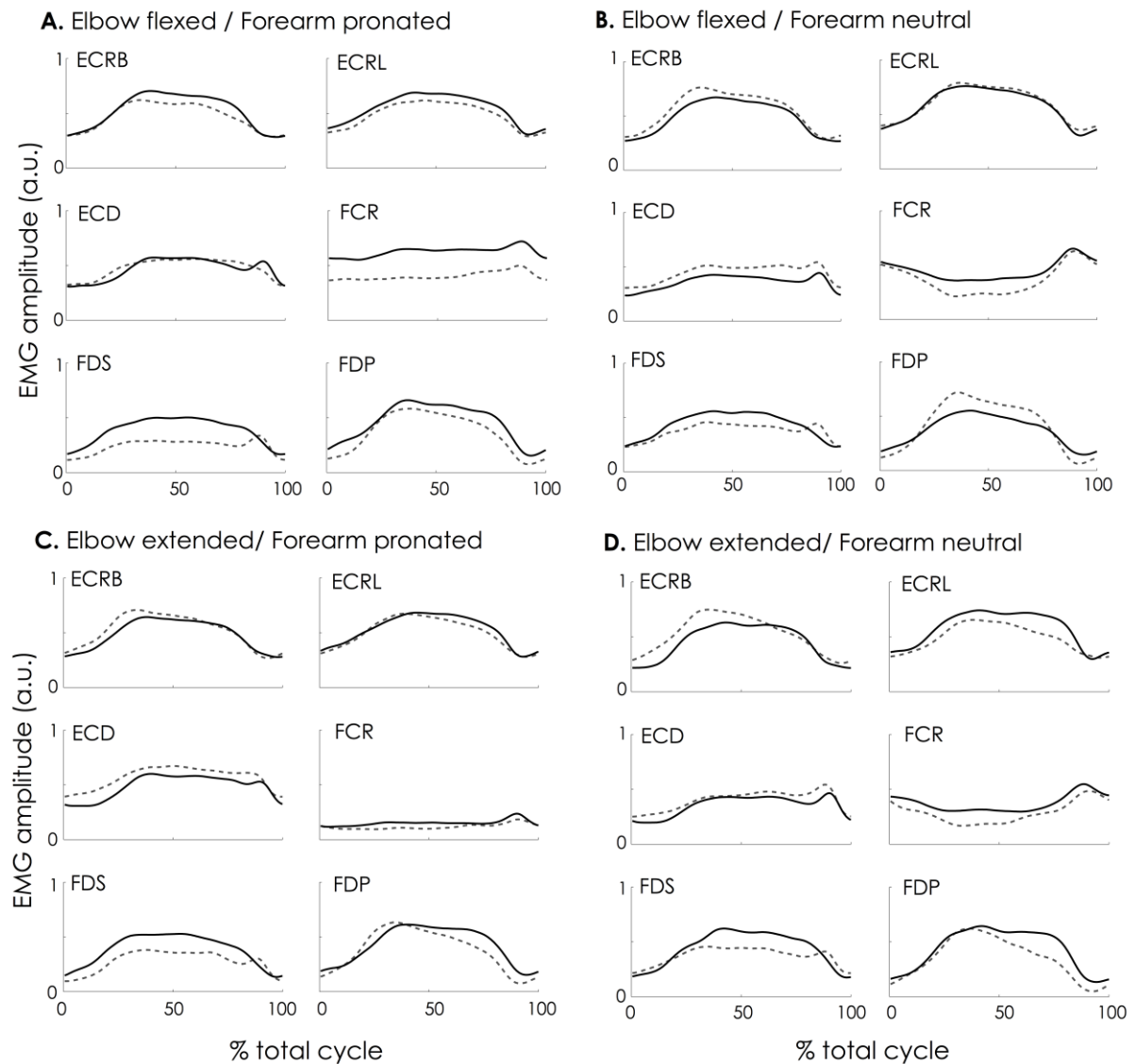


Figure 2. Muscle synergies obtained for each group in each of the four different arm positions (Dotted line and grey bars – LE group, Solid line and black bars – pain-free control group). a.u. – arbitrary units, ECRB – extensor carpi radialis brevis, ECRL – extensor carpi radialis longus, EDC – extensor digitorum communis, FCR – flexor carpi radialis, FDS – flexor digitorum superficialis, FDP – flexor digitorum profundus

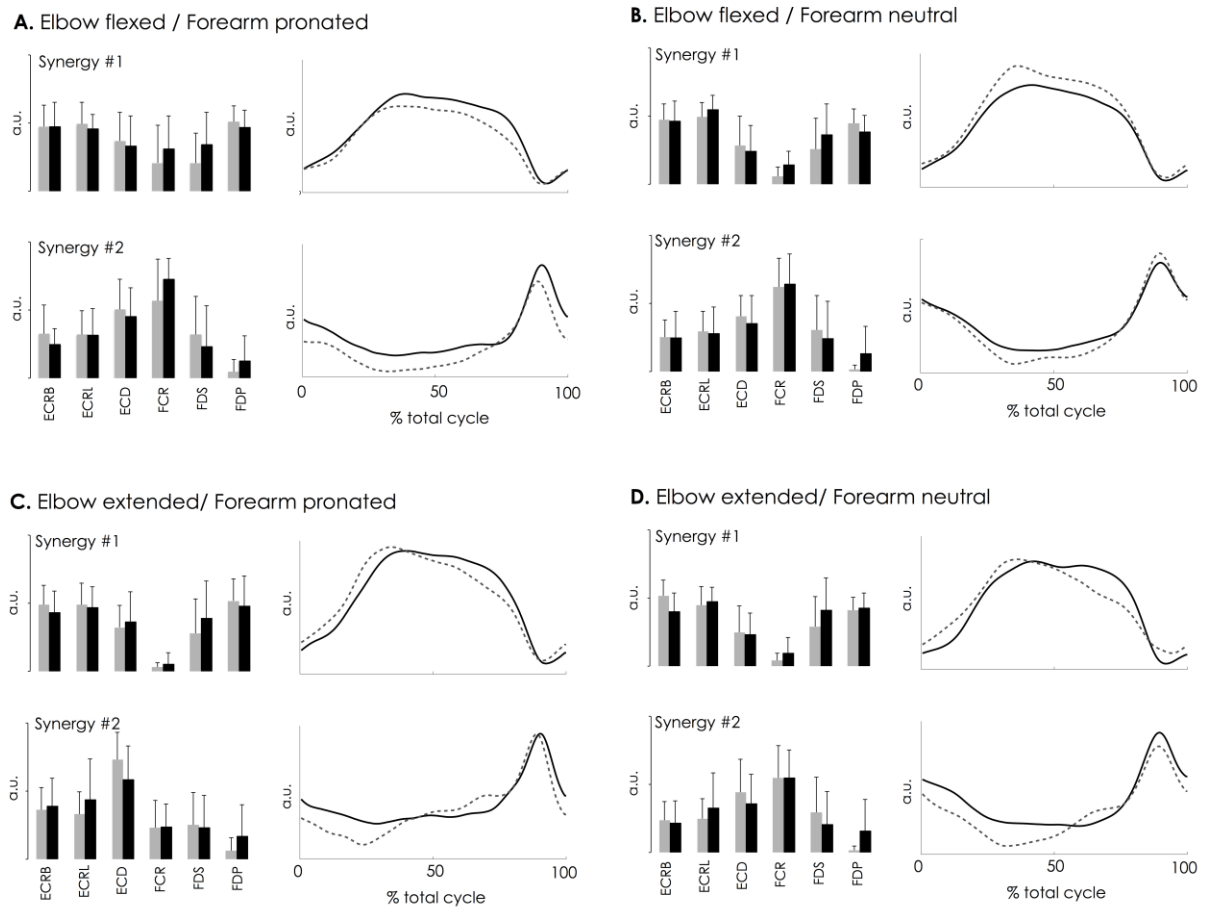


Figure 3. Data for a representative participant with LE (subject #10). The left panel depicts raw data (EMG and grip force) from 3 consecutive cycles. The right panel shows the representative FDS EMG pattern averaged over 12 consecutive cycles. a.u. – arbitrary units, FDS – flexor digitorum superficialis

