



## Spatial reorganisation of muscle activity correlates with change in tangential force variability during isometric contractions



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### ABSTRACT

The aim of this study was to quantify the effects of spatial reorganisation of muscle activity on task-related and tangential components of force variability during sustained contractions. Three-dimensional forces were measured from isometric elbow flexion during submaximal contractions (50 s, 5–50% of maximal voluntary contraction (MVC)) and total excursion of the centre of pressure was extracted. Spatial electromyographic (EMG) activity was recorded from the biceps brachii muscle. The centroids of the root mean square (RMS) EMG and normalised mutual information (NMI) maps were computed to assess spatial muscle activity and spatial relationship between EMG and task-related force variability, respectively. Result showed that difference between the position of the centroids at the beginning and at the end of the contraction of the RMS EMG and the NMI maps were different in the medial–lateral direction ( $P < 0.05$ ), reflecting that muscle regions modulate their activity without necessarily modulating the contribution to the task-related force variability over time. Moreover, this difference between shifts of the centroids was positively correlated with the total excursion of the centre of pressure at the higher levels of contractions ( $>30\%$  MVC,  $R^2 > 0.30$ ,  $P < 0.05$ ), suggesting that changes in spatial muscle activity could impact on the modulation of tangential forces. Therefore, within-muscle adaptations do not necessarily increase force variability, and this interaction can be quantified by analysing the RMS EMG and the NMI map centroids.

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### 1. Introduction

During sustained contractions the muscle activation strategy changes in order to maintain the same force output (Farina et al., 2008). The reorganised muscle activity exposes neural flexibility of motor unit recruitment, suggesting that peripheral and central mechanisms modulate the motor units activation during sustained contractions (Gandevia, 2001). Moreover, new evidence suggests that fatigue effects are uneven distributed over the muscle (Gallina et al., 2011; Hedayatpour et al., 2008), reflecting spatial differences of the motor unit control strategies within the muscle (Farina et al., 2008). The changes in the muscle activity can alter the force output direction (Tucker and Hodges, 2010), leading to modulations of the force variability (Salomoni and Graven-Nielsen, 2012a). Therefore, spatial reorganisation of the muscle activity distribution could yield to modulation of the force variability.

Several reports have tried to associate the changes in motor unit recruitment strategies with changes in force output and its variability (Holtermann et al., 2009; Tucker and Hodges, 2010; Yao et al., 2000). Dissimilarity of motor unit synchronisation behaviour in different locations of the muscle has been positively associated with the force variability (Holtermann et al., 2009). However, several studies have found inconsistencies between motor unit synchronisation and force variability, showing that the contribution of motor unit synchronisation on the force variability is still unresolved (Semmler, 2002). Recent findings suggest that recruitment of additional motor units has a stronger impact in force variability than motor unit synchronisation (Contessa et al., 2009).

Previous studies have focused on unidirectional force variability (Bandholm et al., 2008; Missenard et al., 2009) and recent investigations included three-dimensional force recordings obtaining additional information regarding motor control performance analysing the variability of tangential forces (Salomoni and Graven-Nielsen, 2012a, 2012b; Svendsen and Madeleine, 2010). The muscle contribution to the force output can be estimate by surface electromyography, which is a non-invasive technique assessing global activity of motor unit populations (Disselhorst-Klug et al., 2009; Farina et al., 2004). Spatial information of the

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myoelectric activity can be observed by recording activity from multiple near locations over the same muscle. This spatiotemporal information of muscle activity allows the assessment of adaptations within a muscle (Falla and Farina, 2007; Farina et al., 2008; Gallina et al., 2011; Holtermann et al., 2009).

It is hypothesised that spatial reorganisation of muscle activity modulates force variability during sustained contractions. To test this hypothesis, this study quantifies the relationship between spatial reorganisation of the biceps brachii muscle and task-related/tangential force variability during isometric elbow flexion contractions using linear and nonlinear techniques (Farfán et al., 2010; Madeleine et al., 2011).

## 2. Methods

### 2.1. Subjects

Fourteen right-handed subjects (8 males, age  $26.6 \pm 2.8$  years; height  $170.2 \pm 8.1$  cm; weight  $68.3 \pm 11.9$  kg, mean  $\pm$  SD) were included in the study. Subjects were free of upper limb pain, and they had no history of orthopaedic disorders affecting the upper limb region and no history of neurological disorders. All subjects received written and oral description of the procedures and gave an informed consent consistent with the Declaration of Helsinki ethical standards, and the experimental procedures were approved by the local ethics committee (N-20110079).

### 2.2. Experimental protocol

This study was conducted in a single session where subjects sat upright in a neutral position with their back resting against a height-adjustable chair. The elbow joint of the right arm was flexed at  $90^\circ$  while the forearm was in supinated position, and the wrist was in slight contact with a three-dimensional force transducer, which recorded the force output during elbow flexion (Fig. 1a).

The experiment consisted of isometric submaximal elbow-flexion contractions denominated “three-dimensional” contractions, since subjects were asked to match three force components at 5%, 15%, 30%, and 50% MVC for 50 s. Before the three-dimensional contractions, MVC was recorded by performing two consecutive maximal contractions for 10 s with an interval of 60 s. Thereafter, a set of submaximal contractions 50 s long with 3 min in-between

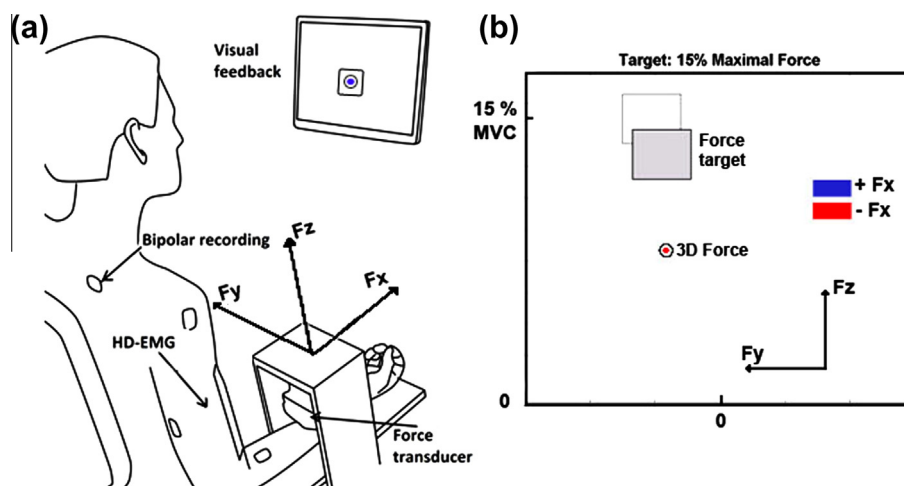
were assessed. In these contractions, only the task-related force component (Fig. 1a: Z direction) was displayed on the visual feedback, while medial–lateral (Fig. 1a: Y direction) and anterior–posterior (Fig. 1a: X direction) force components were recorded. The average magnitudes of the tangential forces recorded were used to set the dimension and position of the target force in the three-dimensional contractions. Finally, the three-dimensional contractions were performed. A continuous visual feedback of the resultant force output (Fig. 1b: circle) was given, as well as the three-dimensional visual force target (Fig. 1b: square). Subjects performed 2 trials of each set of submaximal contractions levels in random order. Only the three-dimensional contractions were used in further analyses. During all the submaximal contractions, the visual feedback showed a ramp-and-hold contraction with 4 s of ramp phase from repose position to the required level of contraction. All motor tasks were followed by 5 min of rest, where subjects were able to move their arm if needed.

### 2.3. Visual feedback

The visual feedback was presented through a two-dimensional plot on a computer screen. Force components parallel with the axial plane of the wrist were represented as a moving black open circle. The open circle position on the Z axis represented the task-related force direction, while the position on the Y axis represented medial–lateral force directions. The remaining X axis was represented by a circle, concentric to the black open circle, showed in red or blue colour to indicate anterior or posterior error of the force output relative to the target force (Fig. 1b). Moreover, the concentric circle radius represented the magnitude of the deviations from the anterior–posterior force target. The force target on the Z and Y axis was represented by a square, which moved on the screen over time during the ramp phase. The size of the square was set to 5% of the Z and Y axes scales for each level of contraction. To fulfil the required motor task, the circle should be inside the square throughout the whole task. The final position of this target was displayed by a dashed square.

### 2.4. Force recordings

The three dimensional force components and torques were measured using a six-axis load cell transducer (MC3A 250, AMTI,



**Fig. 1.** (a) Schematic illustration of the setup. The EMG electrode grid was placed on the biceps brachii muscle, and bipolar electrodes were located on relevant elbow-flexion muscles. Force output was recorded in the task-related (Z) and the tangential (X and Y) directions using a three-dimensional force transducer. (b) Example of the visual feedback provided to subjects. The target force was represented by a moving square in the Fy–Fz plane, and the final position was shown as an additional dashed square. The continuous three-dimensional force output was represented by a black circumference, which moved in the Fy–Fz plane, and a circle which changes colour and size depending on the magnitude and direction on the Fx direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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