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Trunk extensor muscle endurance and its relationship to action potential conduction velocity and spectral parameters estimated using high-density electromyography

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ABSTRACT

Trunk extensor muscle fatigue typically manifests as a decline in spectral content of surface electromyography. However, previous research on the relationship of this decline with trunk extensor muscle endurance have shown inconsistent results. The decline of spectral content mainly reflects the decrease in average motor unit action potential conduction velocity (CV). We evaluated whether the rate of change in CV, as well as two approaches employing the change in spectral content, are related to trunk extensor muscle endurance. Fourteen healthy male participants without a low-back pain history performed a non-strictly controlled static forward trunk bending trial until exhaustion while standing. For 13 participants, physiologically plausible CV estimates were obtained from high-density surface electromyography bilaterally from T6 to L5. Laterally between L1 and L2, the linear rate of CV change was strongly correlated to endurance time ($R^2 = 0.79$), whereas analyses involving the linear rate of change in spectral measures showed a lower ($R^2 = 0.38$) or no correlation. For medial electrode locations, estimating CV and its relationship with endurance time was less successful, while the linear rate of change in spectral measures correlated moderately to endurance time ($R^2 = 0.44$; $R^2 = 0.56$). This study provides guidance on monitoring trunk extensor muscle fatigue development using electromyography.

1. Introduction

With development of trunk extensor muscle fatigue, the power spectrum of the trunk extensor muscles' surface electromyography (EMG) is typically compressed towards lower frequencies, which is usually expressed as a decrease in the median or mean frequency [Roy and De Luca, 1989; van Dieën et al., 1993a].

The rate of decline of these spectral measures has previously been associated with trunk extensor muscle endurance time [Coorevits et al., 2008; Mannion et al., 1997; Mannion and Dolan, 1994; van Dieën et al., 1993a, 1998; van Dieën and Heijblom, 1996]. However, these studies reported inconsistent findings, while studies also reported insufficient repeatability of the rate of decline of spectral measures [Elfving et al., 1999; Larivière et al., 2002; Nargol et al., 1999; Peach et al., 1998; van Dieën and Heijblom, 1996]. Also, a larger sensitivity to changes in electrode location was reported for trunk extensor muscles compared to other muscles with a less complex muscle architecture [Farina et al., 2003]. Besides muscle fatigue, other factors like the vicinity of motor-end plates or tendinous tissue [Farina et al., 2003; Hogrel et al., 1998; Roy et al., 1986] and cross-talk of other back muscles or ECG [Vieira and Botter, 2021], likely affect the spectral content of the trunk extensor muscles. Moreover, during non-strictly controlled trunk extension tasks, large variations in motor unit (MU) recruitment may occur [Farina et al., 2003; van Dieën et al., 1993b]. Altogether, these factors complicate the interpretation of trunk extensor muscle spectral content and its relationship with endurance time.

With the development of muscle fatigue, the decline of spectral measures mainly reflects the decrease in average MU action potential conduction velocity (CV) [Krogh-Lund and Jørgensen, 1992, 1991; Linssen et al., 1993]. Therefore, trunk extensor CV could provide additional insight into development of trunk extensor muscle fatigue [Del Vecchio et al., 2017]. Recently, our research [Brouwer et al., 2022]

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indicated that plausible trunk extensor muscle CV estimates can be obtained during non-strictly controlled, prolonged static bending using high-density surface electromyography (HDsEMG), with a method that relies on estimating the time-delay between individual highly correlated HDsEMG peaks [Beck et al., 2005; Houtman et al., 2003]. However, whether CV changes over time are related to development of trunk extensor muscle fatigue is unknown.

The aim of this study was to evaluate whether the rate of change in CV is related to the development of trunk extensor muscle fatigue (i.e., endurance time) during non-strictly controlled, prolonged static trunk bending. Furthermore, we compared this to the relationship of trunk extensor muscle fatigue with common approaches employing the change in spectral content. The first approach relies on HDsEMG (HDsEMG spectral approach) and thus includes the use of multiple rather than single electrode sites, as suggested in previous research [e.g., Coorevits et al., 2008; Mannion et al., 1997; Mannion and Dolan, 1994]. The second approach is based on conventional single differential EMG (conventional spectral approach) and can be considered more practical. We hypothesized that the rate of change in CV is correlated to the endurance time of a prolonged trunk static bending task. Furthermore, we evaluated whether the relationship with endurance time is similar for CV, HDsEMG-based spectral content, and conventional EMG-based spectral content.

In our previous study, we validated trunk extensor CV estimates from HDsEMG obtained unilaterally from a limited area by comparing peak-delay and cross-correlation methods [Brouwer et al., 2022]. Therefore, before evaluating the relationship between trunk extensor CV and endurance time, we evaluated whether trunk extensor CV estimates can be obtained bilaterally and at other spinal levels.

2. Methods

The experimental procedure and equipment are described in detail elsewhere [Brouwer et al., 2022]. Briefly, fourteen healthy male participants (26.9 ± 5.4 years; 1.79 ± 0.09 m; 74.9 ± 11.7 kg; no history of low-back pain) volunteered for this study after providing written informed consent. The experimental procedure was approved by the Natural Sciences and Engineering Sciences Ethics committee of the University of Twente (reference number: 2020.15). Participants were asked to perform a static bending (30 ± 3 degrees lumbar flexion) endurance trial until exhaustion, while standing with their hip joints fixed using a structure. During the trial, HDsEMG signals were recorded using eight HDsEMG 8x8 electrode grids (AgCl electrodes; electrode diameter: 4.5 mm; inter-electrode distance: 8.5 mm; TMSi, Oldenzaal, The Netherlands), placed bilaterally (four grids per side; starting at the height of the L5 spinous process, Fig. 1AB), and four 128-channel Refa systems (TMSi, Oldenzaal, The Netherlands), storing data at 2048 samples/s. Participants were asked to relax their arms and shoulders to reduce resulting cross-talk from the shoulder muscles. During the trial, participants received real-time visual trunk flexion angle feedback.

2.1. Data analysis

The pre-processing of HDsEMG signals is described in detail elsewhere [Brouwer et al., 2022]. Briefly, the monopolar signals (typically 512 per participant) were filtered using a zero-lag (1) second-order high-pass Butterworth filter with a cut-off frequency of 30 Hz to remove ECG artefacts [Redfern et al., 1993], (2) second-order low-pass Butterworth filter with a cut-off frequency of 500 Hz, and (3) eighth-order Butterworth band-stop filter to remove the 50 Hz power-line interference. The top left grid of participant 6 (i.e., 64 monopolar channels) and seven monopolar channels of participant 5 were excluded due to signal loss.

2.1.1. CV

Per electrode grid with 64 monopolar signals, 48 double differential channels were constructed along the cranial-caudal axis, to attenuate non-traveling potentials [Broman et al., 1985; Farina et al., 2003]. Using a previously described peak-delay method [Brouwer et al., 2022], per pair of neighboring double differential channels, the conduction velocity between individual highly correlated ($R > 0.9$) peaks was estimated along the cranial-caudal axis in both directions separately. Per 10 s, the median conduction velocity was computed to obtain a CV time series. CV time series were excluded if (1) the average CV did not fall within the expected physiological range of CV (2–6 m/s [Arendt-Nielsen and Zwarts, 1989]), or (2) the average peak density was below 40 peaks/10 s [Brouwer et al., 2022]. Additionally, CV time series indicating that estimating CV was only temporarily successful were excluded (peak density below 10 peaks/10 s for more for 2 consecutive median CV estimates or for more than 4 median CV estimates in total; see suppl. fig. S1 for a sensitivity analysis).

For the included CV time series, a linear fit was used to describe the average rate of CV change during the endurance trial [Mannion and Dolan, 1994; van Dieën et al., 1993a]. The linear model was fitted using a least absolute residual regression on the time series of the conduction velocity between individual highly correlated peaks. Subsequently, the goodness-of-fit was evaluated using the mean absolute error (MAE)

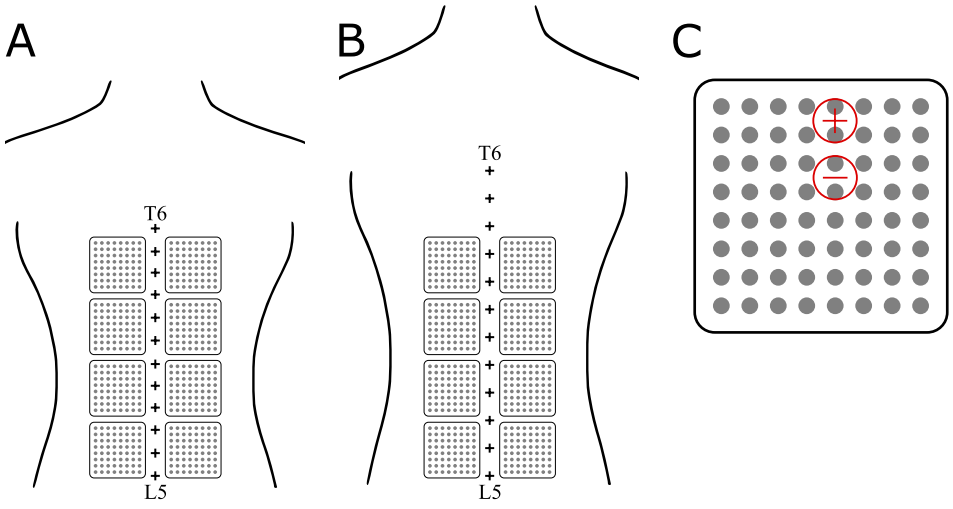

Fig. 1. Schematic illustrations: HDsEMG set-up (participant height: (A) 1.80 m; (B) 2.00 m) and (C) HDsEMG electrode grid with in red an example of a simulated single differential electrode pair (conventional spectral approach). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between the linear fit and the CV time series. CV time series yielding an MAE below 0.5 m/s were considered for further analysis.

2.1.2. Spectral analysis

For the HDsEMG spectral approach, signals from double differential channels were considered. For the conventional spectral approach, two neighboring monopolar HDsEMG signals along the cranial-caudal axis were averaged to simulate a single monopolar EMG signal (approx. surface area assuming a circular electrode: 1.3 cm^2; Fig. 1C). Conventional single differential EMG signals were obtained using two neighboring simulated monopolar EMG signals (approx. inter-electrode distance: 17 mm).

The median frequency (MDF) was computed from the estimated power spectral density for every 2 s (1 s epochs, 50% overlap; Hamming window). Per MDF time series (HDsEMG spectral approach: multiple left and right; conventional spectral approach: one left, one right), a linear fit was used to describe the average rate of MDF change [Mannion and Dolan, 1994; van Dieën et al., 1993a].

2.1.3. Area selection for estimation of relationship with endurance time

Due to the absolute size of the HDsEMG electrode grids, between-participant height differences and the electrode grid placement procedure, the number of available channels for a given spinal level and (to a lesser extent) medial–lateral position was not constant across participants (Fig. 1AB). Hence, for each approach (i.e., CV, HDsEMG spectral approach, conventional spectral approach), a separate topographical map was constructed to obtain the number of available channels (i.e., included CV sites, double differential channels, conventional channels; Fig. 2A, 3AC, 3BD, respectively) across participants for a given spinal level and medial–lateral position. In constructing these maps, the cranial-caudal axis was scaled to the height of the participant using the location of the electrode grids relative to marked spinous processes on a photo. Using these topographical maps, a subset of the data from two bilateral areas was selected for evaluating the relationship with endurance time.

The first bilateral area was defined using the CV topographical map (Fig. 2A) and yielded the highest density of CV sites across participants. This bilateral area was located laterally between the L1 and L2 spinous process, likely over the left and right iliocostalis lumborum muscle [Bogduk et al., 1992; McGill et al., 1993].

The second bilateral area was chosen based on previous studies, which indicated that the rate of MDF change obtained over the longissimus thoracis muscle showed a stronger relationship with endurance time [Coorevits et al., 2008; van Dieën et al., 1993a; van Dieën and Heijblom, 1996] and better repeatability [Larivière et al., 2002] when compared to the iliocostalis lumborum muscle. Hence, this area was

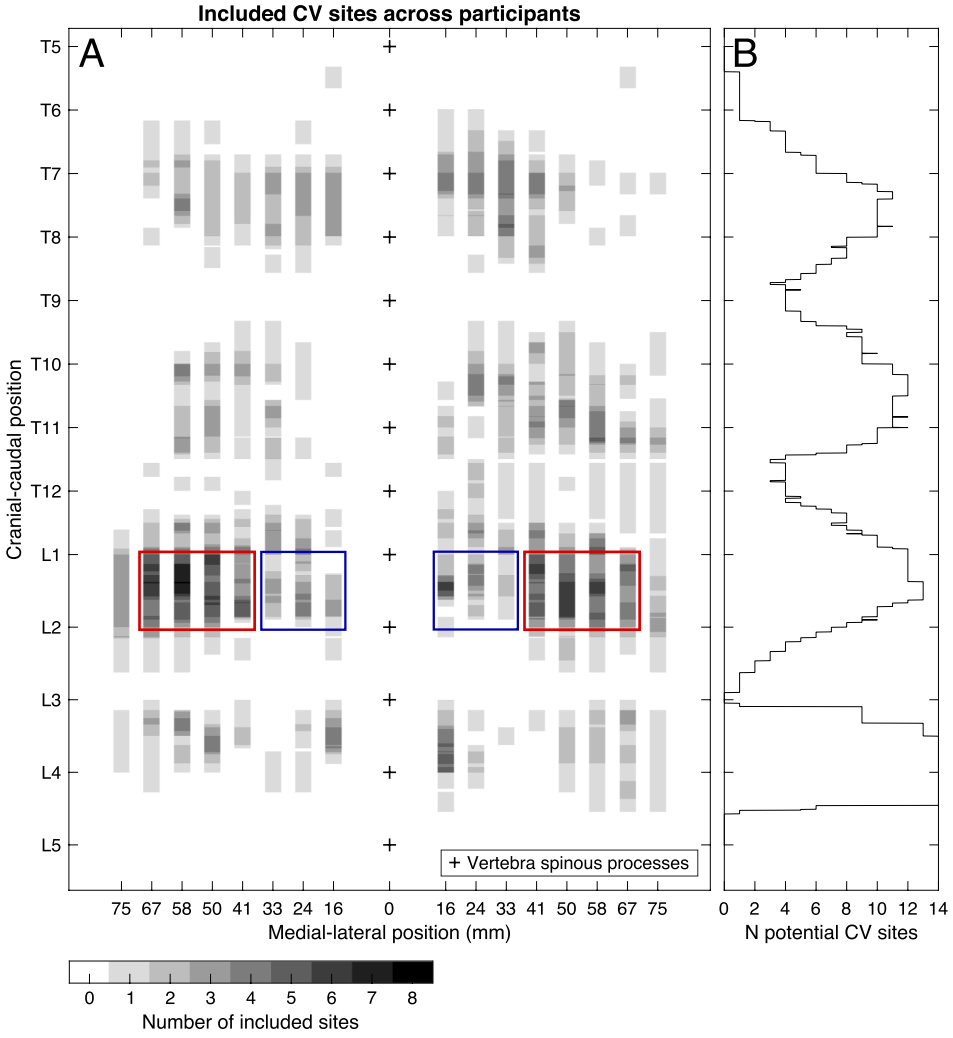

Fig. 2. A: Topographical map of included CV sites across participants (N = 14). Each CV site (depicted as the area between a pair of double differential channels) is scaled along the cranial-caudal axis using the inter-vertebral distance between the vertebrae closest to the considered site. Selected lateral and medial areas are depicted by the red and blue rectangles, respectively. B: number of potential CV sites (i.e., available pair of double differential channels) across participants for a given cranial-caudal position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

defined medially, also between the L1 and L2 spinous process (Fig. 2A), likely over the left and right longissimus thoracis muscle [Bogduk et al., 1992; McGill et al., 1993].

The same area was considered for spectral estimates and for CV estimation, but for the final CV analysis only sites yielding a valid CV estimate were considered. (Fig. 2A). For the HDsEMG spectral approach, per bilateral area, all double differential channels located within the areas considered were selected (Fig. 3AC). So, to simulate an HDsEMG measurement without a-priori CV estimation, the HDsEMG spectral approach included double differential channels both related to CV sites and to sites yielding no CV estimates. Similarly, to simulate a conventional EMG measurement without a-priori CV estimation, for the conventional spectral approach, per bilateral area, the two (one per side) simulated single differential channels located closest to the midpoint between L1 and L2 were selected from the second and third electrode column from the spine for medial and lateral, respectively (Fig. 3BD).

2.2. Statistics

Per bilateral area, linear regressions were performed with endurance time as dependent variable and a single independent variable describing the linear rate of change, namely: mean normalized slopes (slope divided by intercept) of the CV, the HDsEMG-based MDF, and the conventional EMG-based MDF, each for medial and lateral separately. Since normalized slopes are recommended for spectral measures [Farina et al., 2003] and yielded similar or better relationships with endurance time here, only the normalized slopes are reported. Since the precision of the mean CV slope depended on the number of included CV sites and the latter varied across participants, the regressions involving CV were weighted using the standard error of the mean of each participant. Hence, participants yielding only one CV site within the considered area were excluded (Table 1). For consistency, for the HDsEMG and conventional spectral approach, weighted regressions weighted using the standard error of the mean MDF slope were also performed. Participant 11 was excluded for both spectral approaches since normalized MDF slopes were more than 3 times the standard deviation away from the mean.

Table 1
Number of CV sites per participant: from the spinous process of T6 to L5 (bilaterally); within the selected bilateral areas between the L1 and L2 spinous processes. See Fig. 2 for the bilateral areas considered.

Participant	Number of CV sites			Endurance time (s)
	T6-L5	L1-L2		
		Lateral	Medial	
1	82	18	4	1335
2	85	29	8	753
3	72	19	3	1717
4	68	39	19	2378
5	15	0	0	1202
6	87	17	6	1853
7	28	11	4	2421
8	4	0	0	2178
9	33	1	4	1039
10	4	0	0	2366
11	0	0	0	486
12	66	5	5	1425
13	35	8	0	752
14	72	7	2	638
Total	651	154	55	–

3. Results

3.1. CV

In 13 out of 14 participants a total of 684 (out of 4428) CV sites was found (see suppl. fig. S2 for examples of signals containing traveling

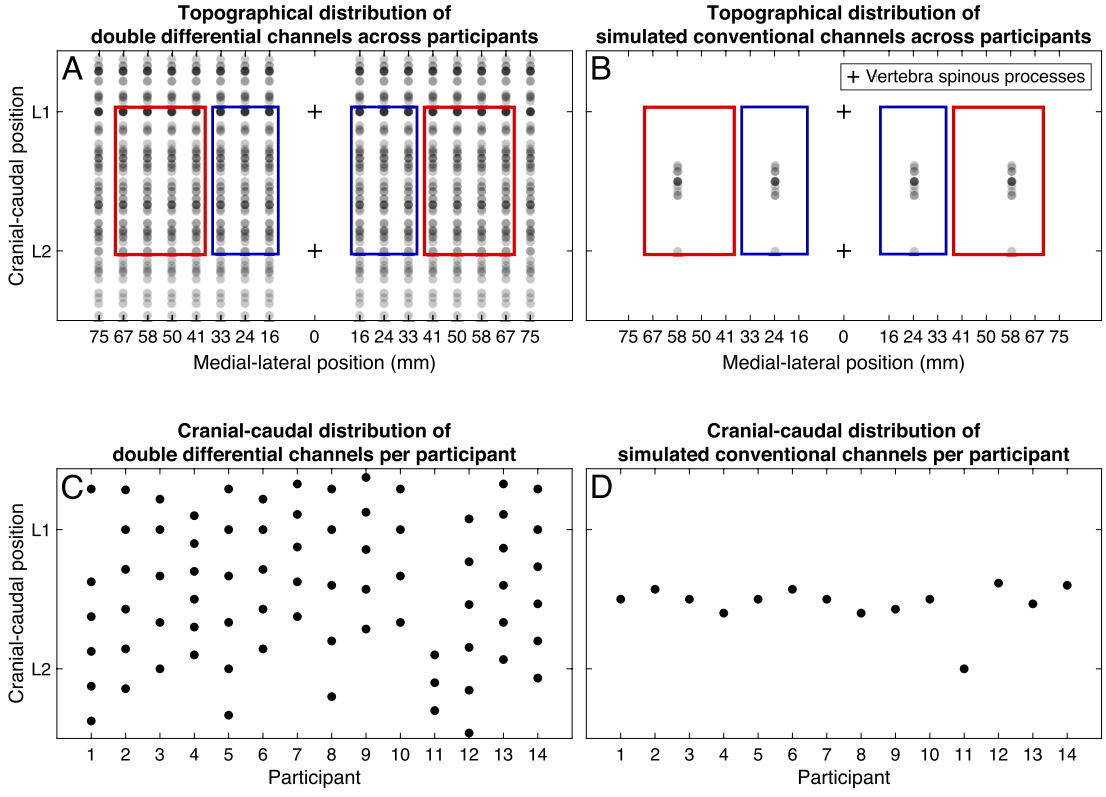

Fig. 3. Topographical map across participants and cranial-caudal distribution per participant of centroids of (AC) double differential channels and (BD) selected simulated conventional channels closest to the midpoint between L1 and L2. Selected lateral and medial areas are depicted by the red and blue rectangles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

potentials). The inclusion criteria regarding gaps in CV time series resulted in excluding CV sites mostly between the T6 and T9 spinous process (i.e., upper bilateral electrode grids; suppl. fig. S3). From these 684 CV sites, a total of 645 indicated cranial-to-caudal propagation and only 39 indicated caudal-to-cranial propagation. 651 sites across 13 participants (for these 13 participants, median: 66 [range: 4–87] sites per participant; see Table 1 for number of sites per participant; see Fig. 2A for spatial distribution of sites) yielded a sufficiently good linear fit to describe the CV change over time (MAE < 0.5 m/s).

3.2. Relationship with endurance time

The bilateral area located laterally between L1 and L2, which yielded the highest density of CV sites across participants, included 154 CV sites across 10 participants (Table 1). The weighted and non-weighted regressions (n = 9) revealed that normalized CV slope was significantly related to endurance time ($R^2 = 0.79$, $p = 0.001$ and $R^2 = 0.77$, $p = 0.002$, respectively) (Fig. 4A; see suppl. fig. S4A for the slopes of individual CV sites; see suppl. fig. S5 for non-normalized slope findings). For the HDsEMG spectral approach (n = 13), normalized MDF slope was significantly related to endurance time (weighted: $R^2 = 0.31$, $p = 0.048$; non-weighted: $R^2 = 0.37$, $p = 0.028$; Fig. 4C). For the conventional spectral approach (n = 13), normalized MDF slope was not significantly related to endurance time (weighted: $R^2 = 0.02$, $p = 0.632$; non-weighted: $R^2 = 0.08$, $p = 0.339$; Fig. 4E).

The bilateral area located medially between L1 and L2 included 55 CV sites across 9 participants (Table 1). The weighted regression for normalized CV slope with endurance time (n = 9) revealed no significant relationship ($R^2 = 0.29$, $p = 0.136$; Fig. 4B). However, the non-weighted regression revealed a significant relationship with endurance time ($R^2 =$

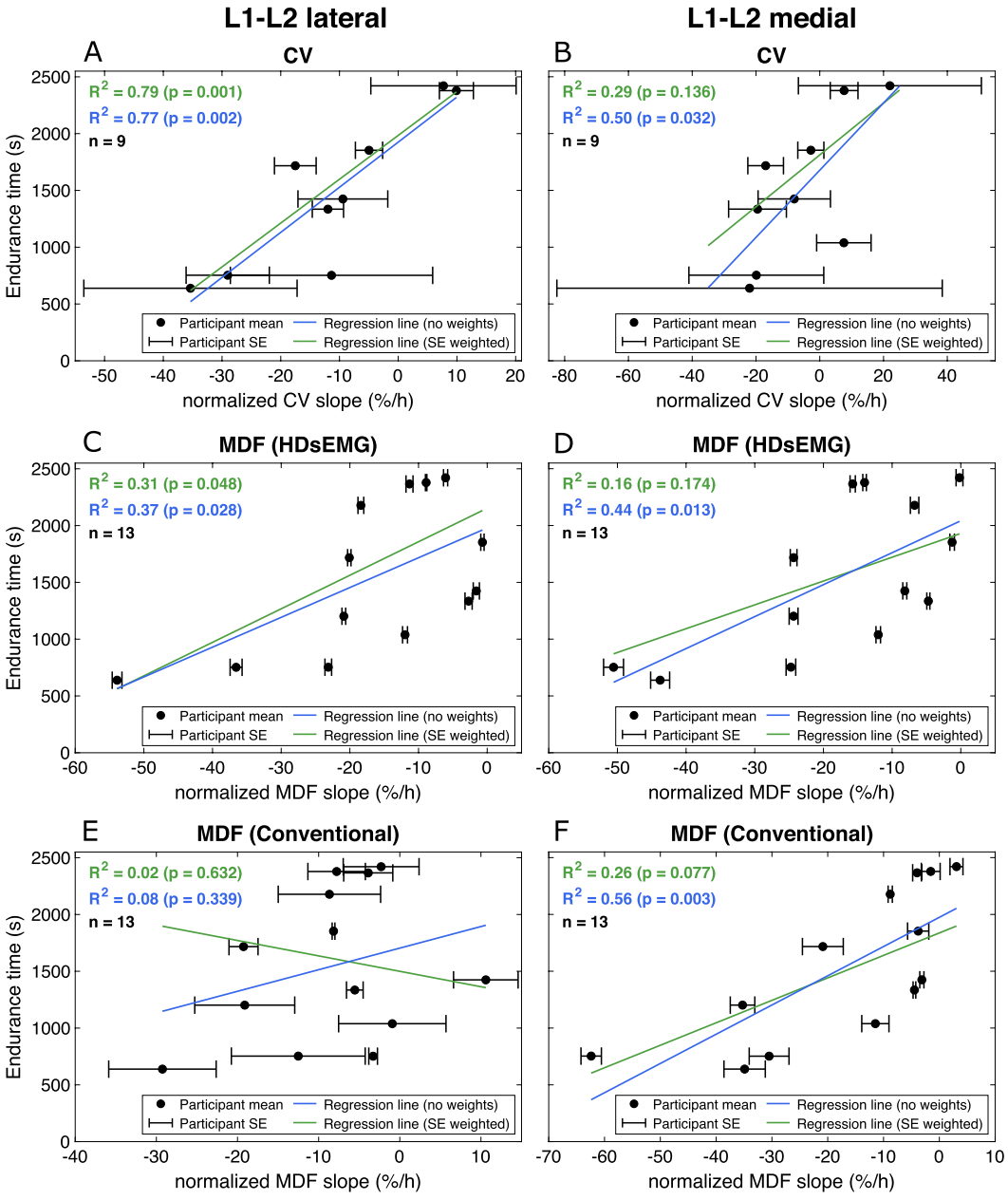

Fig. 4. Relationship of normalized rate of change in conduction velocity (CV) and median frequency (MDF) of high-density surface EMG (HDsEMG) and conventional single differential EMG, with endurance time. The measures were obtained from a bilateral area located laterally (A, C, E) or medially (B, D, F) between the L1 and L2 spinous processes (number of participants in the upper left corner). Weighted regressions (weighted using the standard error of the mean) were also performed since the number of CV sites between-participants varied considerably (Table 1).

0.50, p = 0.032; see suppl. fig. S4B for the slopes of individual CV sites). For both the HDsEMG (n = 13; R^2 = 0.44, p = 0.013; Fig. 4D) and conventional spectral approach (n = 13; R^2 = 0.56, p = 0.003; Fig. 4F), significant relationships with endurance time were found for the non-weighted regression. For both approaches the weighted regression yielded no significant relationship (HDsEMG spectral approach: n = 13, R^2 = 0.16, p = 0.174, Fig. 4D; conventional spectral approach: n = 13, R^2 = 0.26, p = 0.077, Fig. 4F).

4. Discussion

The aim of this study was to evaluate whether the rate of change of the CV and spectral content of trunk extensor EMG, is related to fatigue development during prolonged static trunk bending.

4.1. CV

During this non-strictly controlled task, physiologically plausible trunk extensor CV estimates were obtained bilaterally in 13 (out of 14) participants at spinal levels ranging from approximately T6 to L5 using HDsEMG (Fig. 2A; Table 1). The spatial distribution of excluded CV time series for which CV estimation was only temporarily successful (mostly between T6 and T9; suppl. fig. S3) may imply time-varying activation of the thoracic trunk extensor muscles or cross-talk from shoulder muscles in some participants. The observed propagation direction suggests that innervation zones were mostly located near the cranial musculotendinous junctions, which previously have been difficult to locate for trunk extensor muscles [Barbero et al., 2012; Behringer et al., 2014].

The bilateral area located laterally between L1 and L2, likely over the left and right iliocostalis lumborum muscle [Bogduk et al., 1992; McGill et al., 1993], yielded the highest density of CV sites across participants. At this area, the rate of CV change was strongly correlated to endurance time (Fig. 4A). For the medial area, likely over the left and right longissimus thoracis muscle [Bogduk et al., 1992; McGill et al., 1993], only the non-weighted regression of CV with endurance was significant, with a lower explained variance and number of CV sites than laterally. As discussed previously in more detail [see Brouwer et al., 2022], the reduced number of physiologically plausible CV estimates medially, might be related to a more complex muscle architecture, volume conductor, or a combination of both. Previously we reported that medially a considerable number of sites yielded overestimated CV (i.e., 6–8 m/s) along with high peak density values [Brouwer et al., 2022]. Including these sites (i.e., considering an upper CV threshold of 8 m/s) resulted in including an additional 70 sites and improved the association with endurance time for the weighted regression (R^2 = 0.56, p = 0.008), but worsened the relationship for the non-weighted regression (R^2 = 0.43, p = 0.028), suggesting that overestimated CV estimates may still be used to monitor fatigue.

The within-participant variance in CV slopes may indicate local differences in rates of fatigue development (Fig. 4AB). Furthermore, in participants with a greater endurance time, sites were found yielding a positive CV slope suggesting recruitment of larger MUs or an increase in firing rate of already recruited MUs (see suppl. fig. S6) [Farina et al., 2002]. These observations would confirm previous studies investigating spectral content suggesting additional recruitment of MUs during low-level trunk extensor muscle contractions [Farina et al., 2003; van Dieën et al., 2009, 1998, 1993a, 1993b].

These findings support our first hypothesis that, mainly laterally between L1 and L2, the development of trunk extensor muscle fatigue can be monitored using the linear rate of CV change during a non-strictly controlled prolonged static trunk bending task involving potential additional MU recruitment. The lower number of included CV sites, lower correlation and large within-participant variance in CV slopes medially versus laterally suggest that a sufficient number of CV sites is required to obtain an accurate estimate of fatigue development.

4.2. Spectral content-based approaches

For the analysis of the relationship of the spectral content-based approaches with endurance time we will focus on the non-weighted regression results since, in contrast to the CV, the number of included channels for the HDsEMG and conventional spectral approach was similar and equal across participants, respectively (Fig. 3).

This study indicates that, in contrast to previous research in low-level prolonged contractions [Farina et al., 2003], the development of trunk extensor muscle fatigue can be estimated between L1 and L2 both medially and laterally using HDsEMG in a double differential configuration, albeit with a limited explained variance.

While the dominant factor is CV [Linssen et al., 1993], MU firing statistics also affect the spectral content, mainly below 30 Hz [Krogh-Lund and Jørgensen, 1992, 1991]. With development of fatigue, the latter may explain the typically larger decrease in spectral content when compared to CV [Krogh-Lund and Jørgensen, 1992, 1991]. However, Fig. 4 suggests that spectral content generally did not show a larger decrease than CV, indicating that the 30 Hz high-pass filter (used to remove the electrocardiogram [Redfern et al., 1993]) likely also removed electromyographic manifestations of fatigue-related changes in MU firing (e.g., synchronization) [Krogh-Lund and Jørgensen, 1992, 1991]. This implies that the spectral content was predominantly affected by CV. When compared to CV, the considerably lower correlation between HDsEMG-based spectral content and endurance time at the lateral area suggests other factors may also have affected the spectral content, for example, cross-talk or noise [Farina et al., 2003].

The conventional spectral approach significantly correlated to endurance time at the medial area, but not laterally. For both the iliocostalis lumborum and longissimus thoracis muscles, previous research indicated no relationship between endurance time and slope of spectral measures for contractions below 40 % maximal voluntary contraction (MVC) [van Dieën et al., 1993a] while significant relationships for contractions exceeding 40 % MVC were reported [Coorevits et al., 2008; van Dieën et al., 1993a; van Dieën and Heijblom, 1996]. Comparing endurance times in this study to previous research [Farina et al., 2003; van Dieën et al., 1993a], the present contraction levels were likely below 25 % MVC. So, for predicting trunk extensor muscle endurance time using a conventional electrode configuration during low-level contractions, this study (1) confirms that this is not feasible using iliocostalis lumborum spectral content, and (2) suggests, in contrast to previous research, that this is feasible using longissimus thoracis spectral content.

Laterally the HDsEMG spectral approach outperformed the conventional spectral approach, but not medially. This contrast can be explained by a higher signal-to-noise ratio and less cross-talk medially than laterally, possibly due to a higher %MVC of medial muscles during lumbar extension efforts [Vink et al., 1987]. The difference in results between methods at the lateral area would suggest the need for a larger measurement area than typically considered for a conventional spectral approach [Vieira and Botter, 2021] and for a higher order spatial filter (i.e., double differential instead of single differential), the latter likely reducing cross-talk from the latissimus dorsi muscle.

4.3. Limitations

Given the challenging protocol and the absence of relevant data to compute a-priori sample size, we measured a limitted sample size of 14 participants. Moreover, the participants in the current study likely had a thinner subcutanuous layer, which will have helped to obtain physiologically plausible CV estimates between double differential channels. We used a double differential spatial filter in estimating CV to attenuate non-traveling potentials [Broman et al., 1985; Brouwer et al., 2022], based on previous research reporting that double differential signals resulted in CV estimates closer to what is considered physiollogically plausible than single differential signals [Farina et al., 2003]. A limitation of this higher-order spatial filter is the limited depth of the

measurement volume when compared to lower-order spatial filters. Therefore, the results of the current study may be difficult to generalize. In populations with a thicker subcutanuous layer (e.g., sedentary individuals) estimating CV between double differential channels may be problematic. Future research could evaluate whether also monopolar or single differential channels could be used to estimate trunk extensor muscle CV with the peak-delay method.

Besides muscle endurance, motivation and tolerance of discomfort also affect the endurance time. Between-participant differences in these factors may account for part of the unexplained variance of the computed regressions.

Selecting an area for estimating the relationship with endurance time resulted in a different sample size between CV and the spectral approaches. Hence, regressions were also performed for the CV and HDsEMG spectral approach including all HDsEMG electrode grids, thus including 13 participants in both analyses (Table 1). This revealed a lower and higher explained variance for CV and HDsEMG spectral approaches, respectively, resulting in a similar explained variance between approaches for the non-weighted regression (suppl. fig. S7).

Considering a MAE threshold may have affected the relationship between CV and endurance time. However, adjusting the MAE threshold generally resulted in a change in R^2 of less than 0.10 (suppl. table S1).

4.4. Future research

Future research should evaluate whether, using CV or either of the two spectral approaches, the trunk extensor muscle endurance time can be predicted from data of only a limited part of the total endurance time [e.g., van Dieën et al., 1998], which would be useful in practical applications.

5. Conclusion

For 13 (out of 14) participants physiologically plausible trunk extensor average conduction velocity (CV) estimates were obtained bilaterally for spinal levels ranging from the T6 to L5 spinous process from high-density surface electromyography (HDsEMG). At the bilateral area located laterally between the L1 and L2 spinous process, the linear rate of change in CV was strongly correlated to trunk extensor muscle endurance time. For the same area, the linear rate of change in HDsEMG and conventional EMG spectral measures showed a lower or no correlation to endurance time, respectively, highlighting the need for HDsEMG or a double differential spatial filter. At the bilateral area located medially at the same spinal level, estimating CV and its relationship with endurance time were less successful then laterally. Analyses involving the linear rate of change in spectral measures indicated that medially HDsEMG or complex spatial filters are not required to obtain a moderate correlation with endurance time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2023.102830.

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