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Can intermittent changes in trunk extensor muscle length delay muscle fatigue development?

Niels P. Brouwer [a], Idsart Kingma [a], Wietse van Dijk [b], Jaap H. van Dieën [a,*]

[a] Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, the Netherlands
[b] TNO, Leiden, the Netherlands

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ABSTRACT

Muscle length changes may evoke alternating activity and consequently reduce local fatigue and pain during prolonged static bending. The aim of this study was to assess whether a postural intervention involving intermittent trunk extensor muscle length changes (INTERMITTENT) can delay muscle fatigue during prolonged static bending when compared to a near-isometric condition (ISOMETRIC) or when participants were allowed to voluntarily vary muscle length (VOLUNTARY). These three conditions were completed by 11 healthy fit male participants, in three separate sessions of standing with 30 ± 3 degrees trunk inclination until exhaustion. Conventional and high-density electromyography (convEMG and HDsEMG, respectively) were measured on the left and right side of the spine, respectively. The endurance time for INTERMITTENT was 33.6% greater than ISOMETRIC (95% CI: [3.8, 63.5]; $p = 0.027$) and 29.4% greater than VOLUNTARY (95% CI: [7.0, 51.7]; $p = 0.010$), but not different between ISOMETRIC and VOLUNTARY. The convEMG and HDsEMG amplitude coefficient of variation was significantly greater for INTERMITTENT versus ISOMETRIC. The rate of change in convEMG and HDsEMG spectral content did not reveal significant differences between conditions as found in endurance time. Additional regression analyses between endurance time and rate of change in convEMG ($p > 0.05$) and HDsEMG ($R^2 = 0.39$–0.65, $p = 0.005$–0.039) spectral content indicated that HDsEMG better reflects fatigue development in low-level contractions. In conclusion, imposed intermittent trunk extensor muscle length changes delayed muscle fatigue development when compared to a near-isometric condition or when participants were allowed to voluntarily vary muscle length, possibly due to evoking alternating activity between/within trunk extensor muscles.

1. Introduction

Excessive cumulative low-back load, for instance due to prolonged static bending (Hoogendoorn et al., 2000) in workers performing manual precision tasks (Rohmert and Laurig, 1975), is considered an important risk factor for low-back pain (Coenen et al., 2014, 2013; Norman et al., 1998). Moreover, workers with a limited trunk extensor muscle endurance have an increased risk of developing low-back pain, which suggests that trunk extensor muscle fatigue is a factor in the etiology of low back pain (Biering-Sørensen, 1984; Hamberg-Van Reenen et al., 2006; Luoto et al., 1995; Nicolaisen and Jorgensen, 1985).

Typically, during prolonged contractions, trunk extensor muscle fatigue is associated with restriction of blood flow (Dupeyron et al., 2009; Jensen et al., 1999; Kramer et al., 2005; McGill et al., 2000; Yoshitake et al., 2001). However, during prolonged low-level contractions, trunk extensor muscle fatigue has also been reported without clear signs of blood flow restriction (Kramer et al., 2005; van Dieën et al., 2009). Since sustaining low-level contractions may rely more on an increase in motor unit (MU) firing rate than additional MU recruitment (Søgaard et al., 1998; Tax et al., 1990), small MUs may be exhausted resulting in discomfort and pain (Hägg, 1991, 2000; Jensen et al., 2000; Rosendal et al., 2004; Visser and van Dieën, 2006).

To delay local extensor muscle fatigue development, the central nervous system may utilize the synergistic characteristics of the trunk extensor muscles (van Dieën, 1997) by alternating activity between these muscles (Larivière et al., 2006; Ringheim et al., 2014; van Dieën et al., 1993b). Moreover, during prolonged low-level contractions, MU rotation (i.e., alternating activity between MUs) has occasionally been observed in the trunk extensor muscles (Lothe et al., 2015) as well as in other postural muscles (Jensen et al., 2000; Westad et al., 2003;

* Corresponding author.
E-mail address: j.van.dieen@vu.nl (J.H. van Dieën).

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Westgaard and De Luca, 1999). This would suggest alternating activity between or within the trunk extensor muscles is a possible strategy to reduce local fatigue and pain during prolonged static bending. However, the frequency of alternating activity may differ across individuals and for individuals demonstrating a lower frequency, fatigue develops faster (van Dieën et al., 1993b), and the low-back pain risk is higher (Gerdle et al., 2010; Holtermann et al., 2011).

Muscle length changes may evoke alternating activity between or within the trunk extensor muscles, and thus changes in local muscle loading. In other muscles, during prolonged low-level contractions, changes in muscle length were associated with additional MU recruitment (McNulty and Cresswell, 2004; Søgaard et al., 1998), whereas in isometric contractions increasing firing rate compensated for the decreasing force generating capacity (Pasquet et al., 2005; Søgaard et al., 1998). Additionally, populations of MUs may be recruited at specific muscle lengths only (Nardone et al., 1989), suggesting that a change in muscle length may redistribute muscle activity. Also in the trunk extensor muscles specifically, some MUs were recruited only during specific trunk movements (Abboud et al., 2020).

Using conventional bipolar surface electromyography (EMG), one can estimate the alternating activity between trunk extensor muscles using the EMG amplitude coefficient of variation (Larivière et al., 2006; van Dieën et al., 1993b) and the development of trunk extensor muscle fatigue based on the shift in EMG spectral content (Coorevits et al., 2008; Mannion and Dolan, 1994; van Dieën et al., 1993a; van Dieën and Heijblom, 1996). To also estimate alternating activity within trunk extensor muscles and the global development of trunk extensor muscle fatigue, high-density EMG (HDsEMG) may be employed (Ringheim et al., 2014; Vieira and Botter, 2021).

The aim of this study was to assess whether a postural intervention imposing intermittent trunk extensor muscle length changes can delay the development of muscle fatigue during prolonged static bending and evaluate its effects on conventional EMG and HDsEMG. During prolonged static bending (i.e., maintaining a given trunk inclination), trunk extensor muscle length changes can be established through changes in the ratio of lumbar and hip flexion, the lumbo-hip flexion ratio. In three separate sessions, participants performed a static bending task until exhaustion while standing. In each session the trunk inclination was constant while the lumbo-hip flexion ratio was either (1) fixed at the self-selected ratio (ISOMETRIC); (2) continuously self-selected (VOLUNTARY); or (3) intermittently changed around the fixed self-selected ratio (INTERMITTENT). The endurance time of each session was considered as the primary measure of muscle fatigue development. During the sessions we measured conventional EMG and HDsEMG over the trunk extensor muscles (left and right side of the spine, respectively) to obtain the amplitude coefficient of variation and linear rate of change in spectral content as estimates of alternating activity and muscle fatigue development, respectively. We hypothesized that the endurance time of the static bending task would be longer for INTERMITTENT versus ISOMETRIC and VOLUNTARY, and longer for VOLUNTARY versus ISOMETRIC. Similarly, we hypothesized that, for both conventional EMG and HDsEMG, the amplitude coefficient of variation would be increased and the linear rate of change in spectral content would less decreasing for INTERMITTENT versus ISOMETRIC and VOLUNTARY, and for VOLUNTARY versus ISOMETRIC.

2. Methods

2.1. Participants

Eleven healthy male participants without a history of low-back pain (24.5 $\pm$ 3.6 years; 1.86 $\pm$ 0.05 m; 78.1 $\pm$ 8.4 kg) volunteered for this study after providing their written informed consent. The experimental procedure was approved by the ethical committee of the Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam (reference: VCWE-2021–094). The sample size was based on our previous work (Brouwer et al., 2023) where a similar number of participants was sufficient to detect the development of fatigue using HDsEMG. To obtain sufficient (high-density) EMG signal quality, a thin subcutaneous layer is a major contributor. We therefore only considered young fit male participants and, e.g., no females who typically have a thicker subcutaneous layer in the low-back area.

2.2. Procedure

In three different sessions, participants performed (on average 8 $\pm$ 2.7 days apart, always >4 days) a single endurance trial standing with 30 $\pm$ 3 degrees trunk inclination (Fig. 1). During the endurance trial, participants alternated between one minute performing a precision task (tracking a target on a screen using a pen on a tablet, the target followed an invisible path of six rectangles presented in randomized order) to simulate precision work in a bend posture (see Fig. 1**,** the grey rectangles indicate the precision task sections; see Fig. 2A for the experimental setup) and one minute where participants were asked to relax their arms and shoulders to reduce resulting HDsEMG cross-talk from the shoulder muscles. During all sessions, the precision task was presented on the left side of a screen and on the right side participants received real-time visual postural feedback (Fig. 2A). During the precision task, postural feedback was prioritized (i.e., the precision task would be automatically paused when the target posture was not met). During all conditions, participants received trunk inclination angle feedback (30 $\pm$ 3 degrees). During ISOMETRIC and INTERMITTENT, participants also received pelvis inclination angle feedback. Before ISOMETRIC and INTERMITTENT, the participants' preferred pelvis inclination angle corresponding to 30 degrees trunk inclination was recorded without pelvis inclination angle feedback. For ISOMETRIC, the pelvis inclination angle feedback was equal to the recorded participants' preferred pelvis inclination angle throughout the entire endurance trial. For INTERMITTENT, the feedback-imposed pelvis inclination angle was changed every 2 min (in between two precision tasks; 10 s transition) $\pm$ 5 degrees around their selected preferred angle (Fig. 1). For VOLUNTARY, participants received real-time feedback of the (fixed) trunk inclination angle, but not the pelvis inclination angle, and were informed they were free to continuously select and change their pelvis angle. The order of the conditions was counter-balanced over participants. Participants were instructed to maintain a natural near-extended knee flexion angle during the endurance trial. Before the endurance trial, participants practiced to adjust their pelvis angle, while maintaining a constant trunk inclination. Also, the maximum voluntary contraction (MVC) of the trunk extensor muscles was recorded before the endurance trial to normalize the EMG amplitude during post-processing (McGill, 1991).

2.3. Equipment

After skin preparation (i.e., shaving and cleaning with alcohol), three HDsEMG 8x8 electrode grids (AgCl electrodes; diameter: 4.5 mm; inter-electrode distance: 8.5 mm; TMSi, Oldenzaal, The Netherlands) were prepared with gel and placed 1 cm from the spine, at the right side, stacked with a 1 cm inter-grid distance, starting at the height of the L5 spinous process (Fig. 2BC) (Brouwer et al., 2023, 2022). Conventional EMG pairs were attached at the left side of the spine over the iliocostalis lumborum, longissimus thoracis pars thoracis, and longissimus thoracis pars lumborum muscles (Fig. 2BC) (van Dieën and Kingma, 2005). Conventional single differential EMG and HDsEMG were recorded using one 64 and one 128-channel Refa system (TMSi, Oldenzaal, The Netherlands; CMRR: >90 dB; Input impedance: >100 MΩ; Gain: 26.55; Anti-aliasing: sinc5 filter with a cut-off frequency at 0.2 times the sample frequency) storing each channel digitally at 2048 samples/s. Real-time feedback of trunk and pelvis inclination angles were provided using a custom-made MATLAB script (2019a, The MathWorks, Natick, US) based on inertial measurement units (IMUs; Xsens, Enschede, The Netherlands) attached at the height of the T10 spinous process and at the

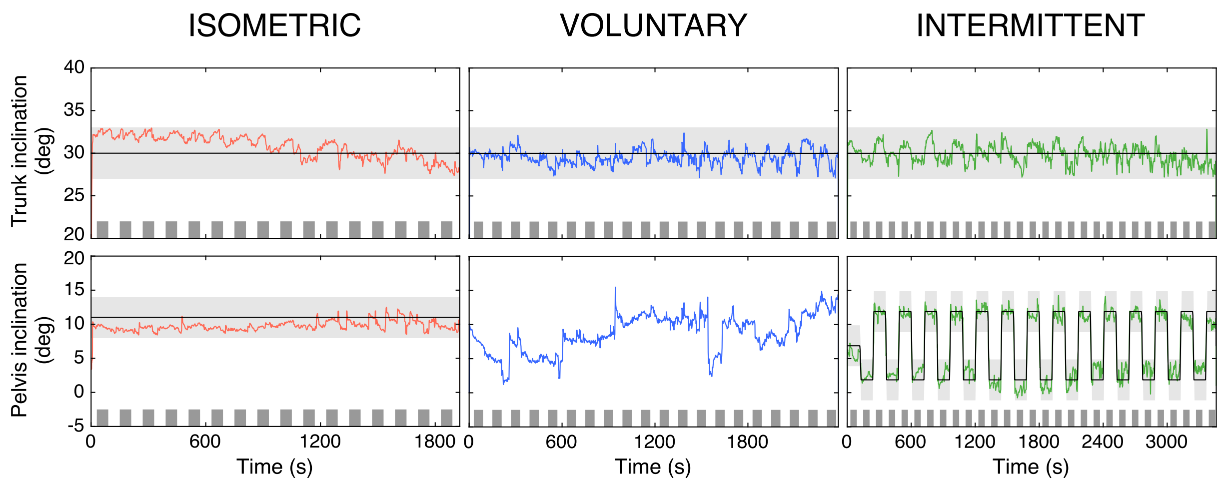

Fig. 1. IMU-based trunk and pelvis inclination angles across conditions (subject 9; endurance time closest to median across conditions). If applicable, the imposed angle and allowed error margin are depicted using the black line and grey area, respectively. The dark grey rectangle depict the time during which the precision task was performed.

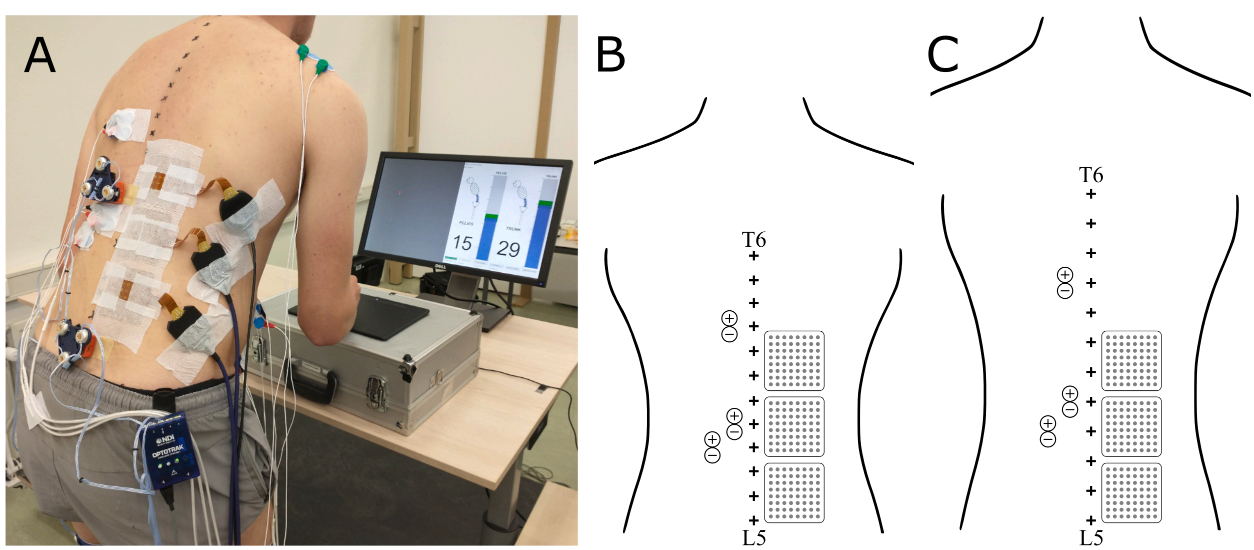

Fig. 2. Experimental set-up. A: participant during an endurance trial while performing the precision task (left half of the screen). The postural feedback (right part of the screen) corresponds to either the ISOMETRIC or INTERMITTENT condition (real-time visual feedback of both pelvis and trunk angle). B and C: Schematic illustration of the high-density and conventional EMG placement (right and left side of the spine, respectively) on participants with a height of 1.80 m (B) and 2.00 m (C).

sacrum (Fig. 2A). Unilateral abdominal single differential EMG, ground reaction forces and moments, and three-dimensional lower extremity, pelvis and trunk kinematics were also measured, however not used in this study.

2.4. Data analysis

The pre-processing of the HDsEMG signals is described in detail elsewhere (Brouwer et al., 2023, 2022). Briefly, the monopolar HDsEMG and conventional single differential EMG signals were filtered using a zero-lag second-order high-pass Butterworth filter with a cut-off frequency of 30 Hz to remove ECG artefacts (Redfern et al., 1993), second-order low-pass Butterworth filter with a cut-off frequency of 500 Hz, and eighth-order Butterworth band-stop filter with to remove the 50 Hz power-line interference (cut-off frequencies 49 and 51 Hz) and its higher harmonics.

In this study, three electromyographic approaches were used: (1) single differential HDsEMG (sdHDEMG); (2) double differential HDsEMG (ddHDsEMG); and (3) single differential conventional EMG (convEMG). For the HDsEMG-based approaches, per electrode grid with 64 monopolar signals, 56 and 48 single and double differential channels were constructed along the cranial-caudal axis, respectively (Brouwer et al., 2023, 2022).

To estimate the linear rate of change in EMG spectral content, the median frequency (MDF) was computed per second from the estimated power spectral density (1 s epochs, no overlap) for all constructed channels (i.e., sdHDsEMG, ddHDsEMG, and convEMG). Subsequently, per approach, all MDF time series (across the three electrode grids or three electrode sites) were averaged to obtain one MDF time series. A linear fit was used to describe the normalized average rate of MDF change over time (i.e., MDF slope divided by the intercept; nMDFslope) (Farina et al., 2003; Mannion and Dolan, 1994; van Dieën et al., 1993a).

The magnitude of alternation of muscle activity was estimated using the coefficient of variation of the EMG amplitude (Ringheim et al., 2014; van Dieën et al., 1993b). Per approach, the root-mean-square amplitude was computed per second and normalized to MVC (nRMS) for each EMG

Table 1
Outcomes of the General Estimating Equations (GEE) analysis to assess differences between conditions in endurance time, self-selected initial pelvis inclination, standard deviation (STD) of detrended (first order polynomial) pelvis inclination and, per EMG approach, the normalized MDF slope (nMDFslope) and coefficient of variation of the normalized root-mean-square amplitude (nRMSCOV). Significant p-values are presented in bold. Note that for the GEE analysis the conditions ISOMETRIC, VOLUNTARY, and INTERMITTENT included 11, 10, and 9 participants, respectively.

	ISOMETRIC	VOLUNTARY vs. ISOMETRIC		INTERMITTENT vs. ISOMETRIC		INTERMITTENT vs. VOLUNTARY	
	Mean [95% CI]	Mean difference [95% CI]	p-value	Mean difference [95% CI]	p-value	Mean difference [95% CI]	p-value
Endurance time (s)	2431 [1792, 3069]	81 [-511, 672]	0.789	817 [92, 1543]	**0.027**	737 [177, 1297]	**0.010**
Initial pelvis inclination (deg)	13.4 [8.4, 18.5]	−1.0 [-3.6, 1.7]	0.482	−2.7 [-5.8, 0.4]	0.088	−1.7 [-3.9, 0.4]	0.111
Pelvis inclination STD (deg)	0.8 [0.7, 0.9]	1.7 [1.1, 2.3]	**<0.001**	3.7 [3.6, 3.9]	**<0.001**	2.1 [1.4, 2.7]	**<0.001**
Single differential HDsEMG							
nRMS (%MVC)	11.9 [9.5, 14.2]	−0.8 [-1.9, 0.2]	0.124	0.8 [-2.0, 3.6]	0.577	1.6 [-1.5, 4.8]	0.314
nMDFslope (%/h)	−10.7 [-16.0, −5.4]	−0.6 [-6.3, 5.2]	0.349	2.3 [-2.6, 7.2]	0.349	2.9 [-0.7, 6.4]	0.110
nRMSCOV (%)	14.8 [11.8, 17.8]	0.8 [-2.1, 3.7]	0.577	4.0 [1.7, 6.3]	**0.001**	3.2 [-0.4, 6.8]	0.083
Double differential HDsEMG							
nRMS (%MVC)	12.9 [11.0, 14.7]	−1.1 [-2.5, 0.2]	0.096	0.6 [-2.4, 3.5]	0.709	1.7 [-1.6, 5.0]	0.320
nMDFslope (%/h)	−10.5 [-15.2, −5.9]	−0.1 [-3.3, 3.1]	0.949	2.0 [-2.3, 6.4]	0.359	2.1 [-2.2, 6.5]	0.335
nRMSCOV (%)	15.5 [12.5, 18.6]	0.6 [-2.8, 4.0]	0.728	3.3 [0.8, 5.9]	**0.011**	2.7 [-1.1, 6.5]	0.160
Conventional EMG							
nRMS (%MVC)	11.0 [8.2, 13.7]	−0.7 [-2.7, 1.3]	0.500	0.4 [-0.9, 1.8]	0.530	1.1 [-1.1, 3.3]	0.325
nMDFslope (%/h)	−5.4 [-12.8, 1.9]	0.4 [-5.0, 5.8]	0.894	3.7 [-3.2, 10.5]	0.293	3.3 [0.3, 6.4]	**0.034**
nRMSCOV (%)	16.7 [12.1, 21.3]	2.2 [-2.1, 6.6]	0.309	5.6 [2.9, 8.2]	**<0.001**	3.3 [-2.1, 8.8]	0.231

channel. Subsequently, per channel, the coefficient of variation was computed by the ratio of the standard deviation of the detrended (i.e., removing the linear trend to avoid effects of gradually increasing amplitude with fatigue development) nRMS to the mean nRMS, times 100 (Ringheim et al., 2014). A single mean coefficient of variation (nRMSCOV) was obtained by averaging over channels (across the three electrode grids or three electrode sites).

Participants 7 and 10 were not able to perform the INTERMITTENT condition since their preferred lumbar flexion angle was close to their extension end of the range of motion. Hence, their data of INTERMITTENT were excluded. Additionally, during VOLUNTARY participant 5 reached flexion-relaxation. Therefore, this data were also excluded.

2.5. Statistics

Generalized Estimating Equations (GEE) were used to assess between-condition differences in endurance time and, per approach, in nMDFslope and nRMSCOV (R Core Team, version 4.2.3, 2013, Vienna, Austria; R package 'gee', version 4.13–25). ISOMETRIC was selected as reference condition. Additionally, per variable, a second GEE was estimated using INTERMITTENT as reference condition to estimate differences between VOLUNTARY and INTERMITTENT. For all GEE analyses the exchangeable working correlation structure was used. Additionally, to assess the relationship of EMG spectral content with the development of trunk extensor muscle fatigue (Brouwer et al., 2023; Mannion and Dolan, 1994; van Dieën et al., 1993a) per approach and per condition, the relationship between nMDFslope and endurance time across participants was evaluated using linear regression (Matlab 2019a, The MathWorks, Natick, US). To assess the between-condition differences in variation in pelvis inclination and initial pelvis inclination, the standard deviation (STD) of the IMU-based pelvis inclination (first order polynomial trend removed) and initial IMU-based pelvis inclination were compared between conditions using GEE. Also, to assess between-condition differences in muscle activity level, for sdHDsEMG, ddHDsEMG, and convEMG, the nRMS was compared between conditions using GEE.

3. Results

Eventually, 11, 10, and 9 participants were included for ISOMETRIC, VOLUNTARY, and INTERMITTENT, respectively. The pelvis inclination STD was significantly higher in INTERMITTENT than in ISOMETRIC and VOLUNTARY. Furthermore, the pelvis inclination STD was significantly higher in VOLUNTARY than in ISOMETRIC (Table 1, Fig. 3A). The initial self-selected pelvis inclination angle was not significantly different between conditions (Table 1, Fig. 3B). Also, for sdHDsEMG, ddHDsEMG, and convEMG, the nRMS was not significantly different between conditions (Table 1).

3.1. Endurance time

The endurance time was significantly higher in INTERMITTENT than in ISOMETRIC and VOLUNTARY (Table 1, Fig. 4BC). In ISOMETRIC the estimated mean endurance time was 2431 s (95% CI: [1792, 3069]), while the estimated mean endurance time in INTERMITTENT was 817 s higher (95% CI: [92, 1543]) or 33.6% (95% CI: [3.8, 63.5]) ($p = 0.027$). Compared to VOLUNTARY, the estimated mean endurance time in INTERMITTENT was 737 s higher (95% CI: [177, 1297]) or 29.4% (95% CI: [7.0, 51.7]) ($p = 0.010$). The endurance time in VOLUNTARY was not significantly different from ISOMETRIC ($p = 0.789$; Table 1, Fig. 4A).

3.2. Normalized MDF slope

For sdHDsEMG and ddHDsEMG, the nMDFslope showed no significant differences between conditions (Table 1, Fig. 5AB). For convEMG,

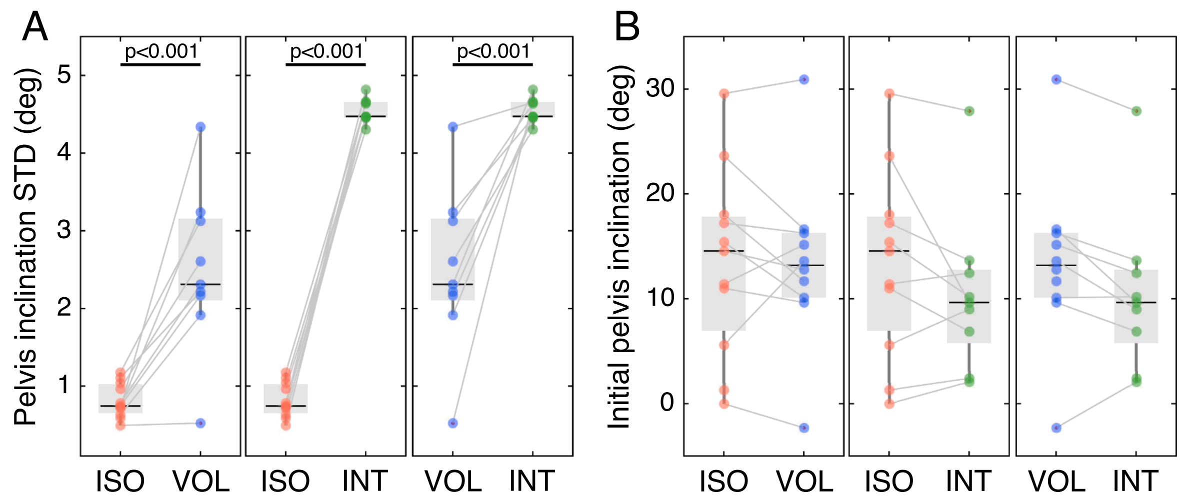

Fig. 3. Pelvis kinematics across conditions ISOMETRIC (ISO), VOLUNTARY (VOL), INTERMITTENT (INT) with (A) the standard deviation (STD) of the detrended (first order polynomial) pelvis inclination and (B) the initial pelvis inclination angle (at the start of the endurance trial at 30 degrees trunk inclination). Per condition, interquartile range (grey box) and median (black line) are depicted. GEE-based significant differences between conditions and corresponding p-values are depicted if applicable.

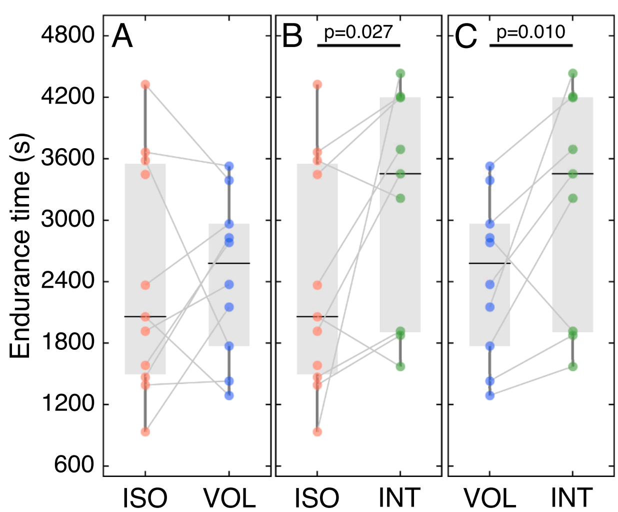

Fig. 4. Endurance time across conditions ISOMETRIC (ISO; n = 11), VOLUNTARY (VOL; n = 10), INTERMITTENT (INT; n = 9). Per condition, interquartile range (grey box) and median (black line) are depicted. GEE-based significant differences between conditions and corresponding p-values are depicted if applicable. Note that the grey lines highlighting the within-participant data points allow for distinguishing the three participants with only 2 included conditions.

the nMDFslope was significantly higher in INTERMITTENT than in VOLUNTARY (Table 1, Fig. 5C), but the nMDFslope in VOLUNTARY and INTERMITTENT were not significant different from ISOMETRIC.

3.3. Normalized RMS amplitude coefficient of variation

For sdHDsEMG, ddHDsEMG, and convEMG, the nRMSCOV was significantly higher in INTERMITTENT than in ISOMETRIC, while the nRMSCOV in VOLUNTARY was not significantly different from ISOMETRIC or INTERMITTENT (Table 1, Fig. 5DEF).

3.4. Relationship between normalized MDF slope and endurance time

For sdHDsEMG, the nMDFslope was correlated to endurance time in all conditions (for ISOMETRIC, VOLUNTARY, and INTERMITTENT: $R^2 = 0.39$, $p = 0.039$; $R^2 = 0.65$, $p = 0.005$; $R^2 = 0.56$, $p = 0.021$; respectively; Fig. 6ADG). For ddHDsEMG, the nMDFslope was correlated to endurance time in ISOMETRIC and VOLUNTARY ($R^2 = 0.37$, $p = 0.048$; $R^2 = 0.46$, $p = 0.030$; respectively; Fig. 6BE), but not in INTERMITTENT ($p = 0.437$; Fig. 6H). For convEMG, for none of the conditions, nMDFslope was correlated to endurance time (for conditions ISOMETRIC, VOLUNTARY, and INTERMITTENT: $p = 0.960$, $p = 0.160$, $p = 0.735$, respectively; Fig. 6CFJ).

4. Discussion

The aim of this study was to assess whether a postural intervention involving intermittent trunk extensor muscle length changes (INTERMITTENT) could delay the development of muscle fatigue during prolonged static bending. In line with our hypothesis, we found that the postural intervention resulted in a significantly greater endurance time by 33.6% (95% CI: [3.8, 63.5]) when compared to a near-isometric condition (ISOMETRIC) or by 29.4% (95% CI: [7.0, 51.7]) when compared to the condition where participants were allowed to voluntarily vary muscle length (VOLUNTARY). This indicates that the postural intervention indeed delayed the development of fatigue. It should be noted that, although a significant effect was found, confidence intervals were rather large, so the size of the effect is difficult to estimate. Furthermore, in contrast to our hypothesis, the endurance time of VOLUNTARY was not significantly different from ISOMETRIC, suggesting that on average participants experienced a similar development of fatigue when they were allowed to voluntarily vary muscle length compared to the near-isometric condition. The sample size may have been too small to find significant differences between these conditions. This finding could also be explained by the large difference in pelvis inclination STD across participants in VOLUNTARY (Fig. 3). Most of the participants showed a larger pelvis inclination STD in VOLUNTARY than in ISOMETRIC. However, the pelvis inclination STD in VOLUNTARY was typically lower than in INTERMITTENT. Furthermore, an additional analysis of the first order polynomial trend (which was removed from the pelvis inclination before computing the STD) of the pelvis inclination angle in VOLUNTARY indicated that in 7 out of 10 participants a backward pelvis tilt (i.e., increasing lumbar angle) over time, thus a shift in load from active trunk extensor muscle tissues to passive trunk extensor muscle and spinal tissues. This is in line with previous research indicating that such a shift tends to develop over time, also in 30 degrees trunk inclination (Alessa and Ning, 2018). In fact, in VOLUNTARY, one participant reached flexion relaxation, thus fully shifting the load from

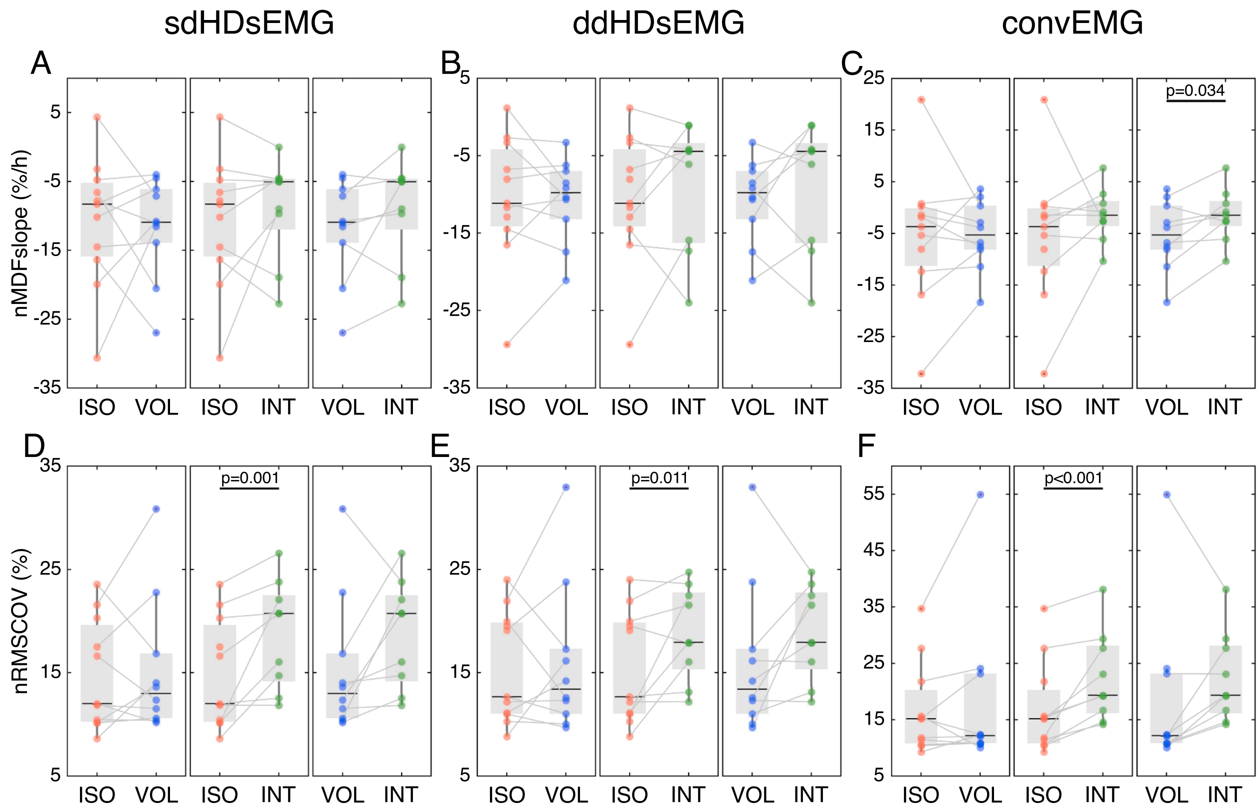

Fig. 5. Per approach EMG (sdHDsEMG (left column), ddHDsEMG (middle column), convEMG (right column)), normalized median frequency slope (nMDFslope; A-C) and coefficient of variation of normalized root-mean-square amplitude (nRMSCOV; D-F). Interquartile range (grey box) and median (black line) are depicted. GEE-based significant differences between conditions ISOMETRIC (ISO; n = 11), VOLUNTARY (VOL; n = 10), and INTERMITTENT (INT; n = 9) and corresponding p-values are depicted if applicable. Note that the grey lines highlighting the within-participant data points allow for distinguishing the three participants with only 2 included conditions.

active to passive tissues. Although such a strategy may be metabolically beneficial, delay muscle fatigue and therefore increase endurance time, it may also increase spinal load, creep, and potentially pain in the long-term (Alessa and Ning, 2018; Coenen et al., 2013).

For all EMG approaches, in line with our hypothesis, nRMSCOV was significantly different between ISOMETRIC and INTERMITTENT, indicating that alternating activity was larger in INTERMITTENT. This may have contributed to the greater endurance time in INTERMITTENT (Ringheim et al., 2014; van Dieën et al., 1993b). We would argue that in INTERMITTENT the intermittent muscle length changes may have evoked alternating activity between MUs recruited at different muscle lengths (Abboud et al., 2020; Nardone et al., 1989). Previous studies suggested MU rotation as a strategy to delay muscle fatigue during low-level static contractions (Jensen et al., 2000; Lothe et al., 2015; Westad et al., 2003; Westgaard and De Luca, 1999). In the current study the muscle activity level (10–14%MVC) may have been too high to elicit MU rotation during static phases of the contractions (Bawa and Murnaghan, 2009). Despite a greater endurance time in INTERMITTENT compared to VOLUNTARY, the difference in nRMSCOV between these conditions did not reach significance (Table 1). In addition, nRMSCOV was not different between ISOMETRIC and VOLUNTARY. Both of these findings did not confirm our hypotheses. This may be explained by the range of different pelvis kinematics in VOLUNTARY (Fig. 3A). For example, one participant showed a much higher nRMSCOV in VOLUNTARY versus INTERMITTENT (Fig. 5DEF), likely due to the participant's large pelvis inclination STD (Fig. 3A; upper data point in VOLUNTARY).

For the sdHDsEMG and ddHDsEMG approaches, nMDFslope was not significantly different across conditions and thus did not reflect the delayed development of fatigue in INTERMITTENT versus ISOMETRIC and VOLUNTARY as indicated by the endurance time. Yet, the HDsEMG-based approaches correlated with endurance time, for sdHDsEMG in all conditions and for ddHDsEMG in ISOMETRIC and VOLUNTARY (Fig. 6). The unexplained variance in the relationship between the HDsEMG-based nMDFslope and endurance time in combination with the limited sample size may explain the not significantly increased (i.e., less decreasing) nMDFslope in INTERMITTENT versus ISOMETRIC and VOLUNTARY (Table 1). For convEMG, a significant difference in nMDFslope between VOLUNTARY and INTERMITTENT was found. However, since the convEMG-based nMDFslope was not correlated to endurance time (thus rate of muscle fatigue development), this difference may not be particularly relevant. Previous studies reported generally good correlation between convEMG-based nMDFslope and endurance time of trunk extensor muscles during higher intensity contractions (Coorevits et al., 2008; Mannion and Dolan, 1994; van Dieën et al., 1993a; van Dieën and Heijblom, 1996). However, during low-level contractions this correlation may be reduced or non-existent (Brouwer et al., 2023; van Dieën et al., 1993a). The sdHDsEMG-based nMDFslope appeared to consistently correlate with endurance time in all conditions, outperforming the ddHDsEMG and convEMG approaches. This would indicate that the measurement of a large volume of the muscle (i.e., large number of sensors and no higher-order spatial filter) is required to accurately estimate trunk extensor muscle fatigue development during low-level prolonged contractions, in line with recent recommendations (Vieira and Botter, 2021).

A few limitations of this study should be noted. Besides muscle capacity, motivation and tolerance of discomfort also affect the endurance time (Mannion et al., 2011). Between-session differences in these factors may have affected the endurance time results, however, due to counterbalancing the design, likely only to a limited extent. Furthermore, between-participant differences in these factors may account for part of

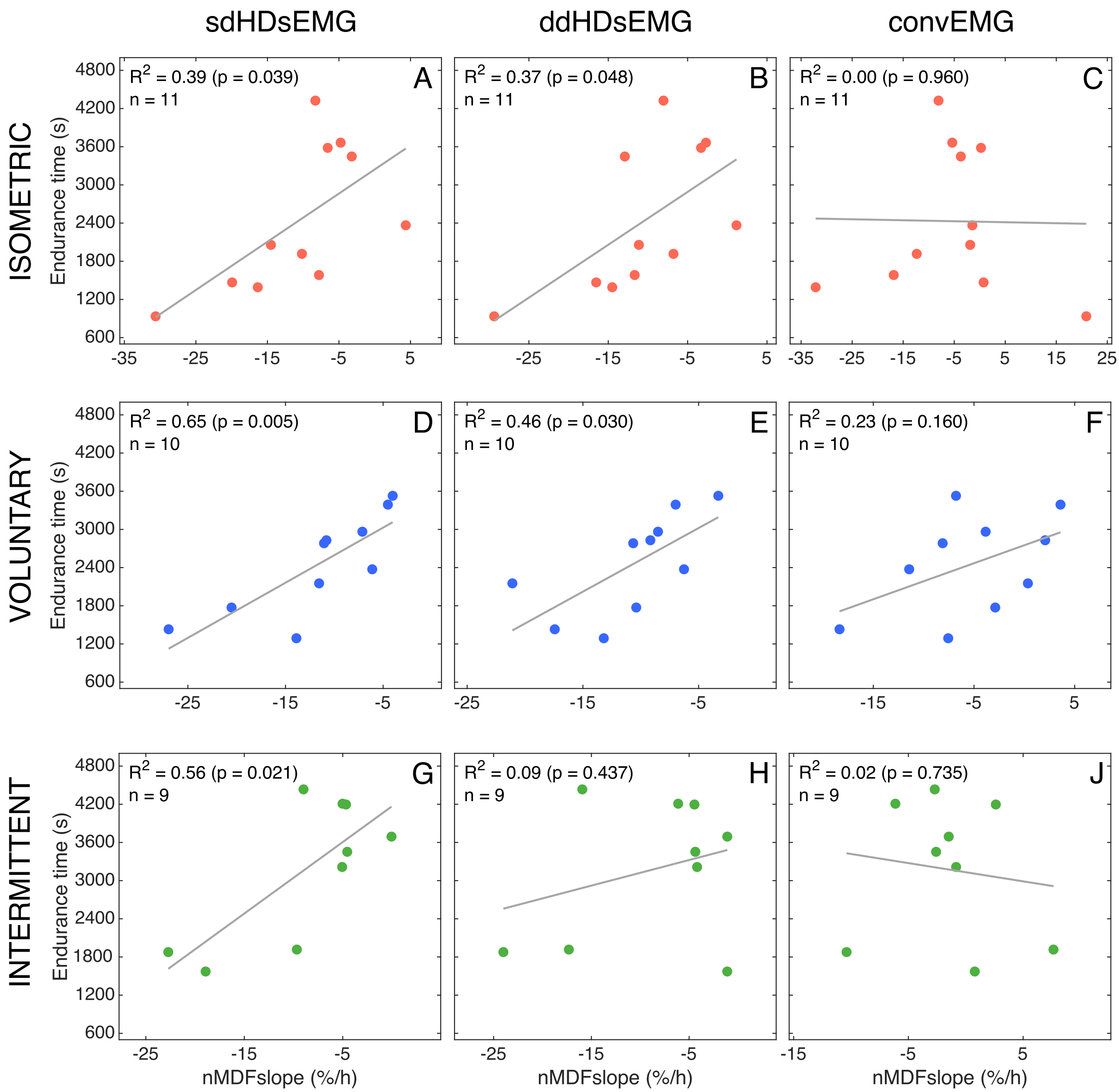

Fig. 6. Per EMG approach (sdHDsEMG (left column), ddHDsEMG (middle column), convEMG (right column)) and per condition (ISOMETRIC (n = 11), VOLUNTARY (n = 10), and INTERMITTENT (n = 9) in red (top row), blue (middle row), and green (bottom row), respectively), the linear regression between endurance time and the normalized median frequency slope (nMDFslope). The R^2, p-value and number of participants are presented in the upper left corner. Note that the grey lines highlighting the within-participant data points allow for distinguishing the three participants with only 2 included conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the unexplained variance of the computed regressions between endurance time and nMDFslope. Compared to ISOMETRIC and VOLUNTARY, the intermittent change in pelvis inclination in INTERMITTENT may have distracted the participants more from discomfort, fatigue and pain. However, we can confirm the participants were highly motivated and would like to suggest that the effect of a 10 sec transition was likely limited. Moreover, participants intermittently performed a precision task in all conditions, and this was likely more effective to distract from discomfort, fatigue and pain. In addition, the participants in this study were rather uniform (young, fit, male) which may limit generalizing certain results. Especially the HDsEMG-based prediction of endurance time using nMDFslope may be more difficult in populations with a thicker subcutaneous layer.

An intervention involving intermittent trunk extensor muscle length changes could be implemented using postural feedback or active trunk exoskeletons (de Looze et al., 2016). In the latter case, these changes could be imposed through a combination of hip and lumbar torques. Such an intervention would not affect the end-point position (e.g., head or hand). When implementing such intervention, one should consider the trunk extensor range of motion. Two participants selected a pelvis inclination close to the extension end of their lumbar range of motion and were therefore not able to meet the imposed intermittent changes in pelvis inclination in INTERMITTENT. Furthermore, one could also consider that muscle length in itself may affect fatigue development and endurance time (e.g., Kooistra et al., 2005). Given the large variation in pelvis inclination with a given trunk inclination across participants (Fig. 3B), in line with previous research (Alessa and Ning, 2018), one might ask whether individuals selected an (initial) muscle length to maximize endurance time.

In conclusion, we found that, in young fit males, a postural intervention involving intermittent trunk extensor muscle length changes resulted in a greater endurance time, thus delayed the development of muscle fatigue, during prolonged static bending when compared to (1) a near-isometric condition or (2) when participants were allowed to voluntarily vary muscle length. Furthermore, endurance time was not different between the near-isometric condition and the condition in which participants were allowed to voluntarily vary muscle length. The variation in trunk extensor muscle activity, estimated using conventional and high-density electromyography, indicated that the postural intervention evoked alternating activity between or within the trunk extensor muscles. While our analyses indicated that, in contrast to conventional EMG, the rate of change in spectral content of high-density EMG is associated with trunk extensor muscle fatigue development, this measure did, in contrast to endurance time, not yield the significant differences across conditions.

CRediT authorship contribution statement

Niels P. Brouwer: Conceptualization, Data curation, Writing - original draft, Writing - review & editing, Visualization, Investigation, Formal analysis, Methodology, Project administration and Software. **Idsart Kingma:** Conceptualization, Funding acquisition, Writing - review & editing, Investigation, Formal analysis, Methodology, Supervision. **Wietse van Dijk:** Writing - review & editing, Investigation, Formal analysis, Supervision. **Jaap H. van Dieën:** Conceptualization, Funding acquisition, Writing - review & editing, Investigation, Formal analysis, Methodology, Supervision.

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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