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Reliability of high-density surface electromyography for assessing characteristics of the thoracic erector spinae during static and dynamic tasks

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ABSTRACT

Purpose: To establish intra- and inter-session reliability of high-density surface electromyography (HDEMG)-derived parameters from the thoracic erector spinae (ES) during static and dynamic goal-directed voluntary movements of the trunk, and during functional reaching tasks.

Methods: Twenty participants performed: 1) static trunk extension, 2) dynamic trunk forward and lateral flexion, and 3) multidirectional functional reaching tasks on two occasions separated by 7.5 ± 1.2 days. Muscle activity was recorded bilaterally from the thoracic ES. Root mean square (RMS), coordinates of the barycentre, mean frequency (MNF), and entropy were derived from the HDEMG signals. Reliability was determined with intraclass correlation coefficient (ICC), coefficient of variation, and standard error of measurement.

Results: Good-to-excellent intra-session reliability was found for all parameters and tasks (ICC: 0.79-0.99), whereas inter-session reliability varied across tasks. Static tasks demonstrated higher reliability in most parameters compared to functional and dynamic tasks. Absolute RMS and MNF showed the highest overall reliability across tasks (ICC: 0.66-0.98), while reliability of the barycentre was influenced by the direction of the movements.

Conclusion: RMS and MNF derived from HDEMG show consistent inter-session reliability in goal-directed voluntary movements of the trunk and reaching tasks, whereas the measures of the barycentre and entropy demonstrate task-dependent reliability.

1. Introduction

Trunk muscles are activated in goal-directed voluntary movements, such as flexion, extension, and rotation of the trunk. They are also involved in assisting movements of the upper and lower extremities. For example, trunk muscles are activated during functional reaching (St-Onge et al., 2011) as well as during walking (Anders et al., 2007). Paraspinal muscles cover several segments of the spine and are innervated by spinal nerves from multiple levels (Henson et al., 2019). As a result, activation of the trunk muscles at different spinal levels may differ during single movements (Abboud et al., 2020). Indeed, prior work using bipolar electromyography (EMG) over different regions of the erector spinae (ES) found differential activation between the thoracic and the lumbar region of the ES during goal-directed voluntary movements of the trunk (Coorevits et al., 2008a; McGorry et al., 2001), sitting (O'Sullivan et al., 2006), and perturbations to the trunk (Vera-Garcia et al., 2006). This differential activation of the ES during trunk movements has also been reported in clinical populations. For example, an altered distribution of activity in thoracic and lumbar regions of the ES was observed in people with low back pain during trunk movements (Falla et al., 2014; Lariviere et al., 2000; Sanderson et al., 2019a; van Dieën et al., 2003), sustained contractions (Sanderson et al., 2019b), sitting (Dankaerts et al., 2004), and in people with hip osteoarthritis during walking (Moreside et al., 2018). These findings highlight the importance of detecting regional changes in activity of the paraspinal muscles when evaluating neuromuscular function of the trunk.

While conventional bipolar EMG is commonly used to assess trunk muscle activity, with acceptable inter-session reliability (Brandt et al.,

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2017; Coorevits et al., 2008b; Dankaerts et al., 2004), this EMG methodology provides little information regarding activation patterns of regions within muscles, which can be important for the assessment of trunk muscle behaviour (Vieira & Botter, 2021). High-density surface EMG (HDEMG) utilises a multichannel recording system that can record regional activation within a muscle which enables extraction of spatio-temporal features of the muscle (Falla & Gallina, 2020; Gallina et al., 2013). This specificity of the methodology is particularly suitable for investigation of neuromuscular function of paraspinal muscles (i.e., ES) which consist of muscle fibres covering several levels of the spine (Henson et al., 2019). There have been a number of studies applying HDEMG to investigate the control of the lumbar ES in healthy adults (Abboud et al., 2015; Tucker et al., 2009), and in people with low back pain (Falla et al., 2014; Martinez-Valdes et al., 2019; Murillo et al., 2019; Sanderson et al., 2019a; Sanderson et al., 2019b). However, the test–retest reliability of HDEMG in the ES during goal-directed voluntary movements and functional movements of the trunk has not been established. A previous study monitored changes in HDEMG signals of lumbar paraspinal muscles when participants held the body position in trunk extension until task failure and reported good reliability in the spatial distribution of muscle activity in response to fatigue (Abboud et al., 2015). However, it remains unknown whether HDEMG can provide reliable measurements in the thoracic paraspinal muscles which are activated during dynamic and functional movements of the trunk (e.g., forward flexion, reaching). This information is important for the clinical application of HDEMG measurements of the trunk muscles, for example, before and after an intervention.

The overall aim of this study was to establish the intra- and inter-session reliability of HDEMG parameters recorded from the thoracic ES bilaterally during goal-directed voluntary contractions of the trunk muscles and during multidirectional reaching tasks in healthy adults. Acquiring muscle activity from the thoracic ES was chosen to form a basis for upcoming studies, thereby ensuring reliability of the measures taken. We hypothesised that HDEMG provides reliable intra- and inter-session results in both goal-directed and functional tasks of the trunk.

2. Methods

2.1. Participants

Twenty healthy participants were recruited from the University of Birmingham (age 27.9 ± 4.9 years; mass 68.25 ± 11.08 kg; height 169.5 ± 8.5 cm; 10 males; 18 right-handed; body mass index 23.65 ± 2.85). Exclusion criteria were any known history of neurological or musculoskeletal disorders or a recent (<6 months) history of low back pain. The study was approved by the University of Birmingham's Science, Technology, Engineering and Mathematics Ethical Review Committee (ERN_20-1453) and was conducted in accordance with the Declaration of Helsinki. All participants gave written informed consent prior to data collection.

2.2. Experimental procedures

All participants attended the laboratory on two occasions (between-session interval: 7.5 ± 1.2 days) on approximately the same time of day. The interval between sessions was based on previous HDEMG reliability studies who used the same time between sessions (Gallina et al., 2016; Martinez-Valdes et al., 2016). The participants' height and mass were measured prior to performing the following tasks in each session: 1) static trunk extension, 2) reverse trunk extension (by lifting the legs

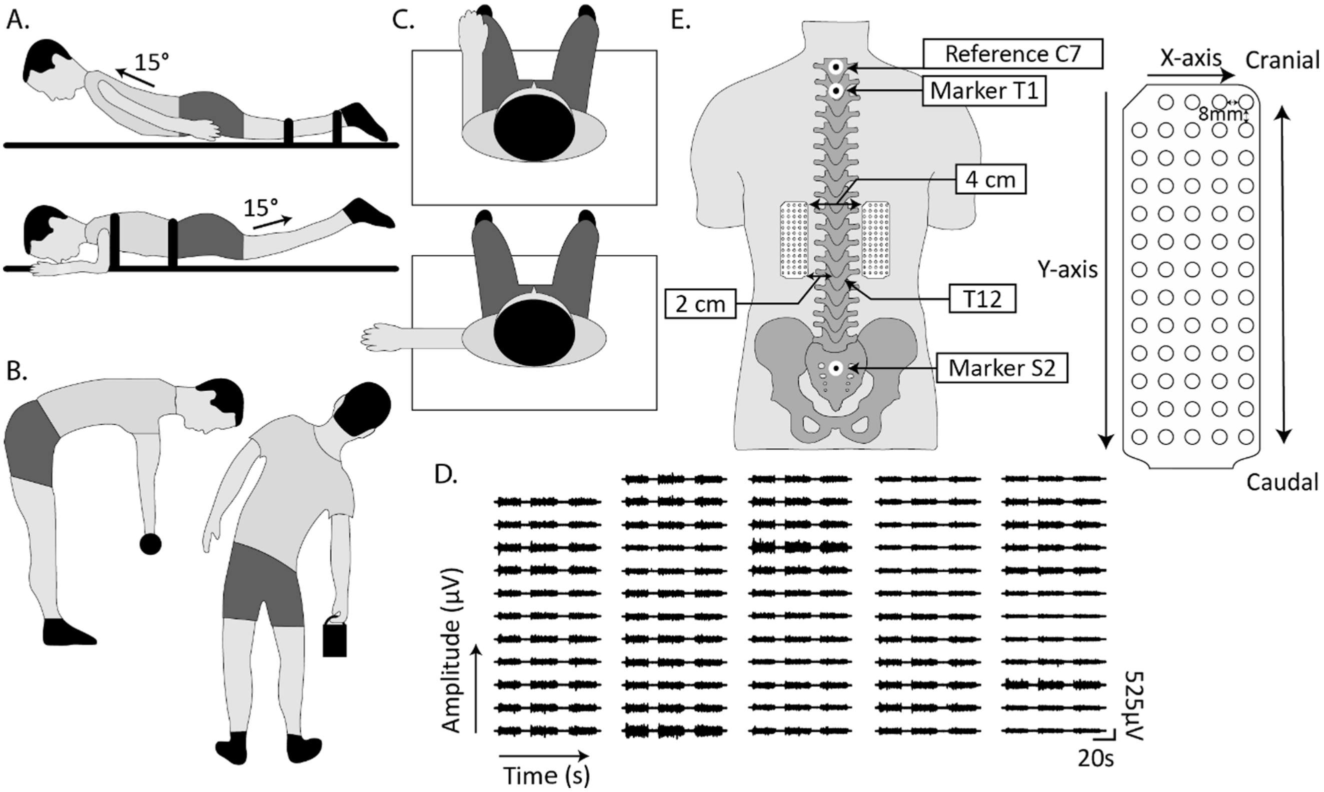

Fig. 1. Experimental setup. (A) Static trunk extension (top) and reverse trunk extension (bilateral leg lift; bottom) to 15° of range of motion. (B) Dynamic trunk flexion (left) and lateral flexion (right) with a weight ~ 5 % of the participant's body mass during the tasks. C) Multidirectional reaching tasks to the front (top) and lateral sides (bottom). (D) Raw differential high-density surface electromyography (HDEMG) activity traces recorded during the static trunk extension task. (E) Placement of HDEMG electrode grids. Grids are placed over bilateral ES, two centimetres lateral from the 12th thoracic spinous process and covered to approximately the 8th thoracic spinous process. Reflective markers are placed bilaterally on the ulnar styloid processes, and on the first thoracic- and second sacral spinous processes.

bilaterally), 3) dynamic trunk flexion, 4) dynamic trunk lateral flexion, and 5) multidirectional functional reaching tasks (forward and lateral reaching) (Fig. 1). Tasks in all sessions were performed in a semi-random order where static tasks were followed by the dynamic tasks, followed by functional tasks. Instructions were given to avoid excessive physical activity between sessions. All measurements were carried out by the same experimenter who was sufficiently trained prior to any data collection to identify spinous processes for electrode placement. Identification of the correct spinous processes was confirmed by a physical therapist with seven years of experience.

For the static trunk extension and reverse trunk extension tasks (Fig. 1A), participants were placed in prone on a plinth with their arms by the sides for static trunk extension, and arms positioned next to the head for reverse trunk extension. To isolate the movements, straps were used to secure the knees and ankles (static trunk extension task), and the upper body (reverse trunk extension task). An additional strap was used to keep both ankles together during the reverse trunk extension task. Participants were asked to perform trunk extension or hip extension from 0° to 15°, maintain the body or legs in the position for 20 s, and then return to the starting position, three times. For those who were unable to perform hip extension to 15° in a prone position ($n = 7$), they were asked to extend their hip joints to their maximal range of motion (10.86° ± 1.46) for 20 s. The range of motion was confirmed by a manual goniometer using the angle between pelvis and the first thoracic spinous process as reference points for the trunk extension task, and the angle between greater trochanter and popliteal fossa for reverse trunk extension. In addition, the distance from the sternum (trunk extension task) or the patella (reverse trunk extension task) to the plinth was measured. These measurements were used to ensure tasks were performed consistently within and between sessions. Self-phased breaks of approximately 20 s were given between each repetition of the tasks to avoid fatigue. A modified CR-10 Borg Scale (0–10), with zero being fully relaxed and ten being the maximal effort (Borg, 1998), was used to document the intensity of the tasks perceived by the participants. The absence of fatigue was ensured by giving the participant sufficient rest between each contraction, and the next trial only started after the score of the CR-10 Borg Scale had returned to their baseline level. For EMG normalisation purposes, two brief (~3 s) maximal voluntary contractions (MVCs) of the trunk extensors without biofeedback were obtained in a prone position (Chiou et al., 2018; Coenen et al., 2017; Dankaerts et al., 2004) with the pelvis and legs firmly secured on the plinth with straps, and manual resistance provided over the scapulae by the same experimenter.

For dynamic trunk flexion and trunk lateral flexion (Fig. 1B), participants stood with their feet shoulder width apart, holding a weight ~ 5 % of the body mass with both hands (trunk flexion) or left/right hand (lateral flexion). The purpose of the added weight was to increase activation of the ES during the tasks, in order to improve the signal-to-noise ratio (Lariviere et al., 2000). Previous studies applied a weight of 10 % of the body mass or ~ 12 kg to induce muscle fatigue (Abboud et al., 2015; da Silva et al., 2015). To minimise muscle fatigue, we chose a weight that was manageable and had minimal influence on task performance. From the participant's neutral standing position, they were asked to flex the trunk forward or to the left/right at their own pace until their maximal range of motion was reached before returning to the starting position and to repeat this five times. The distance from the weight to the floor was measured to ensure consistency of the movements within and between sessions.

For the multidirectional functional reaching tasks (Fig. 1C), participants were seated upright on a custom-made chair with an embedded force plate without back support, the knees positioned in a 90-degree angle, and the feet flat on the floor. Participants were asked to reach forward with their dominant arm or reach to the left/right with their left/right arm as far as possible before returning to the starting position and to repeat this five times.

2.3. Data acquisition

Electromyographic signals were recorded from the thoracic ES bilaterally using two disposable rectangular-shaped surface electrode grids (GR08MM1305, OT Bioelettronica, Turin, Italy) with 64 channels each (1 mm diameter of each channel, 13 rows × 5 columns grid size, 8 mm interelectrode distance, Cu + chemical gilding). Each grid was prepared by first applying a double-sided adhesive foam matrix (Spes Medica, Genoa, Italy). Cavities were then equally filled with conductive paste (AC Cream, Spes Medica, Genoa, Italy). The participant's skin was shaved if needed and prepared with abrasive skin cleaner (Nuprep Skin Prep Gel, Weaver and Company, CO, USA), followed by alcohol skin wipes (GAMA Healthcare, Hertfordshire, UK) to remove any residue left on the skin. The grids were placed over the ES, two centimetres lateral from the centre of the 12th thoracic spinous process and covered to approximately the 8th thoracic spinous process (Fig. 1D). Distance from the grids to bodily landmarks were measured to ensure consistent placement of the grids for the subsequent session. Reference electrodes (Ambu WhiteSensor WS, Ballerup, Denmark; 36 mm × 40 mm) were placed over C7 and bilateral iliac crest. Tape was used to secure wires and pre-amplifiers. Signals were recorded in monopolar mode on a Quattrocento (OT Bioelettronica, Turin, Italy) amplifier with a sampling frequency of 2048 Hz, 150 gain, 10–500 Hz bandpass filter with a 3 dB cut off frequency, input resistance $> 10^{11}\ \Omega$, common mode rejection ratio > 95 dB, noise level referred to input $< 4\ \mu V$, and converted from analogue to digital form using the amplifier's 16-bit converter. Signals were stored on a local computer using OT Biolab software (OT Bioelettronica, Turin, Italy) for further processing.

Movements during dynamic and functional reaching tasks were recorded using an 8-camera 3-D optical motion capture system (Smart DX 6000, BTS Bioengineering Corp, Quincy, MA, USA) operating at 250 Hz to confirm consistency of the task performance within and between sessions. Reflective markers were placed bilaterally on the ulnar styloid process to measure reaching distance, and on the first thoracic- and second sacral spinous processes to calculate range of motion of the trunk (Field-Fote & Ray, 2010). Data acquisition of the HDEMG and motion capture system was synchronised via a 5-volt TTL signal.

2.4. Data analysis

All data processing was performed in MATLAB 2021a (Mathworks, Natic, MA, USA) following previously described procedures (Martinez-Valdes et al., 2019; Sanderson et al., 2019b). Prior to signal analysis, all signals were visually inspected to remove channels with noise or motion artefacts (1.94 channels removed on average across subjects and sessions). A second-order bandpass digital Butterworth filter (10–350 Hz) was then applied to remaining channels. Trial windows for computation of HDEMG parameters were set at 20 s for static tasks. For dynamic and functional tasks, trial windows were based on the starting and end points of the movement, derived from motion markers (see details below).

For the static trunk extension and reverse trunk extension tasks, the beginning and end of a repetition was defined as the time at which participants had maintained 15° of trunk or hip extension, respectively, for 20 s. For the dynamic trunk movements and functional reaching tasks, kinematic data were used to detect the beginning and end of each repetition to guide analysis of the HDEMG. For the dynamic trunk flexion and lateral flexion, the start and end of the movement were detected using the markers in the frontal and sagittal plane, respectively. Degrees of trunk flexion and lateral flexion were calculated in BTS software (SMART Capture, Quincy, MA, USA) from a straight line that was drawn between reflective markers on the sacrum and T1 and compared with a vertical reference line. The range of motion was separated into a flexion phase, and a return to neutral phase (i.e., extension) where participants returned to zero degrees of trunk flexion since approximately half of the participants showed decreased ES muscle activity when approaching the maximal flexion position, which is known as the flexion-relaxation phenomenon (Colloca & Hinrichs, 2005). For the multidirectional functional reaching task, the start and end of the reaching movement were identified by the wrist marker; maximal displacement of the wrist marker was calculated for each repetition as the reaching distance.

Absolute amplitudes of differential root mean square (RMS) were calculated from the monopolar channels for each repetition and rendered in a 12 × 5 muscle activation map, minus the missing channel in the top-left corner (59 channels in total; Fig. 1E). The maximal RMS amplitude obtained from each MVC was calculated (window size 1 *sec*) and the highest RMS value of the two repetitions was used to calculate normalised RMS. Horizontal (x-axis: medial–lateral) and vertical (y-axis: cranial-caudal) coordinates of the barycentre, mean frequency (MNF), and entropy were derived from the grid's channels. Barycentre corresponds to the centre of weighted activity of the muscle measured. MNF denotes the average result of the power spectrum of HDEMG, and its frequency divided by its total power spectrum (Phinyomark et al., 2012). Modified entropy was calculated according to methodologies reported by Farina et al. (2008) as:

$Entropy = -\sum_{i=1}^{59} p^2(i)\ \log_2\ p^2(i)$ where $p^2(i)$ represents the square of the channel's RMS value of i normalised by the sum of squares of the 59 RMS values. Entropy is a measure of the uniformity of muscle activation; a higher value means a greater uniformity of activity of the muscle measured.

2.5. Statistical analysis

Statistical analysis was performed in SPSS version 27 (IBM Corp., Armonk, NY, USA). Paired-t tests were used to compare the angles of trunk flexion and lateral flexion as well as the reaching distance between the sessions. If the assumption of a normal distribution was violated, a Wilcoxon signed-rank tests was used. Coefficient of Variation (CoV%) and Standard Error of Measurement (SEM) were included as measures of absolute reliability. CoV was calculated as $\left(\frac{Standard\ deviation}{Mean}\right) \times 100$ to determine the normalised variability across subjects within and between sessions. A low CoV indicates a more reliable measurement, while a high CoV is related to a less reliable measurement (Shechtman, 2013). A precise cut-off threshold for CoV has not been defined, but previous studies have used > 20 % CoV as unacceptable (Albertus-Kajee et al., 2010; Martinez-Valdes et al., 2016). The SEM represents differences in measurement units, taking into account both the inter-variation within individuals and the variability of the measurement (Atkinson & Nevill, 1998), and was obtained from the residual error of a within-subject analysis of variance (ANOVA).

Intraclass Correlation Coefficient (ICC), a measure of relative reliability, was calculated using a two-way mixed effects model with absolute agreement. The following criteria were used to determine reliability: < 0.5 poor, 0.5 – 0.75 moderate, 0.75 – 0.9 good, and > 0.9 excellent (Koo & Li, 2016). Intra-session reliability analysis was performed on the three repetitions of static trunk extension tasks, and on the three middle repetitions of dynamic and functional tasks. Data of the three repetitions of each task from each session were averaged to allow for calculation of inter-session reliability. For static trunk extension, dynamic trunk flexion and forward reaching tasks, HDEMG parameters obtained from left and right thoracic ES were averaged since no differences in the amplitude of RMS EMG were found between sides. For dynamic trunk lateral flexion and lateral reaching tasks, the HDEMG parameters obtained from the thoracic ES contralateral to the movement direction were used; for example, in the lateral reaching to the left, EMG of the right thoracic ES was analysed. P-values < 0.05 were interpreted as significant.

3. Results

Representative raw EMG traces and the spread of scores for each HDEMG parameter are presented in Figs. 2 and 3, and reliability results are reported in Table 1 (intra-session) and Table 2 (inter-session). Note that the dynamic trunk flexion and lateral trunk flexion tasks were separated into a flexion phase and a return to neutral phase (i.e., extension).

3.1. Static trunk extension tasks

The angles of trunk or hip extension and distance from the sternum or patella to the plinth were identical between the sessions for the static trunk extension and reverse trunk extension tasks, respectively. Excellent intra-session reliability for static trunk extension and reverse trunk extension was found across parameters (ICC: 0.91 - 0.99; Table 1).

Inter-session reliability revealed good-to-excellent reliability for the absolute RMS, x-axis barycentre, y-axis barycentre, and MNF (ICC: 0.84 - 0.98). Moderate reliability was found for entropy (ICC: 0.64 - 0.66). Normalised RMS showed poor-to-moderate inter-session reliability (ICC: 0.21 - 0.59), with SEM values showing errors ranging from 6.3 % for trunk extension to 16.3 % for reverse trunk extension (Table 2).

3.2. Dynamic trunk flexion tasks

A Wilcoxon signed-rank test and t-tests revealed no significant difference between the two sessions in the angles of trunk flexion (Z = -0.49, p =.63), left lateral flexion ($t(19)$ = -0.65, p =.52), or right lateral flexion ($t(19)$ = 0.19, p =.85).

For trunk flexion, intra-session reliability of the flexion and extension (return to neutral) phases were similar (Table 1). Reliability was good-to-excellent for all parameters (ICC: 0.87 - 0.97). Furthermore, inter-session reliability results demonstrated moderate-to-excellent reliability for the absolute RMS, normalised RMS, y-axis barycentre, and MNF (ICC: 0.73 - 0.93). Inter-session reliability was poor for the x-axis barycentre and for entropy (ICC: 0.23 - 0.49); however, the SEM values of entropy were within 0.11 arbitrary units (Table 2).

For trunk lateral flexion, intra-session reliability was similar between the lateral flexion and return to neutral phases (Table 1). Reliability was good-to-excellent for all parameters (ICC: 0.79 - 0.94). Furthermore, inter-session reliability was moderate-to-good for the absolute RMS, normalised RMS, and MNF (ICC: 0.66 - 0.89), and poor-to-moderate for entropy (ICC: 0.49 - 0.51). Interestingly, inter-session reliability of the barycentre demonstrated the opposite pattern to trunk flexion, with moderate reliability for the x-axis barycentre (ICC: 0.50 - 0.65) and poor-to-moderate reliability for the y-axis barycentre (ICC: 0.23 - 0.53). Nevertheless, inter-session SEM values for entropy and x-axis barycentre were low, while SEM for y-axis barycentre ranged from 2.39 mm to 3.28 mm (Table 2).

3.3. Multidirectional functional reaching tasks

After the initial visual inspection, HDEMG data obtained from one participant during forward reaching and two participants during lateral reaching were removed due to movement artefacts. Paired-t tests showed no significant differences in the distance of forward reaching ($t(18)$ = 0.50, p =.62), left reaching ($t(18)$ = -1.56, p =.14) or right reaching ($t(18)$ = -1.93, p =.07) between the two sessions.

For forward and lateral reaching, intra-session ICC revealed good-to excellent reliability for all parameters (ICC: 0.80 - 0.99; Table 1). Inter-session reliability was good-to-excellent for the absolute RMS and MNF (ICC: 0.86 - 0.93), but poor-to-moderate for the normalised RMS (ICC: 0.42 - 0.59). Reliability of the barycentre was dependent on reaching direction. For forward teaching, excellent and moderate reliability were found for the x-axis barycentre (ICC: 0.94) and y-axis barycentre (ICC: 0.60), respectively. Conversely, for lateral reaching, moderate and good

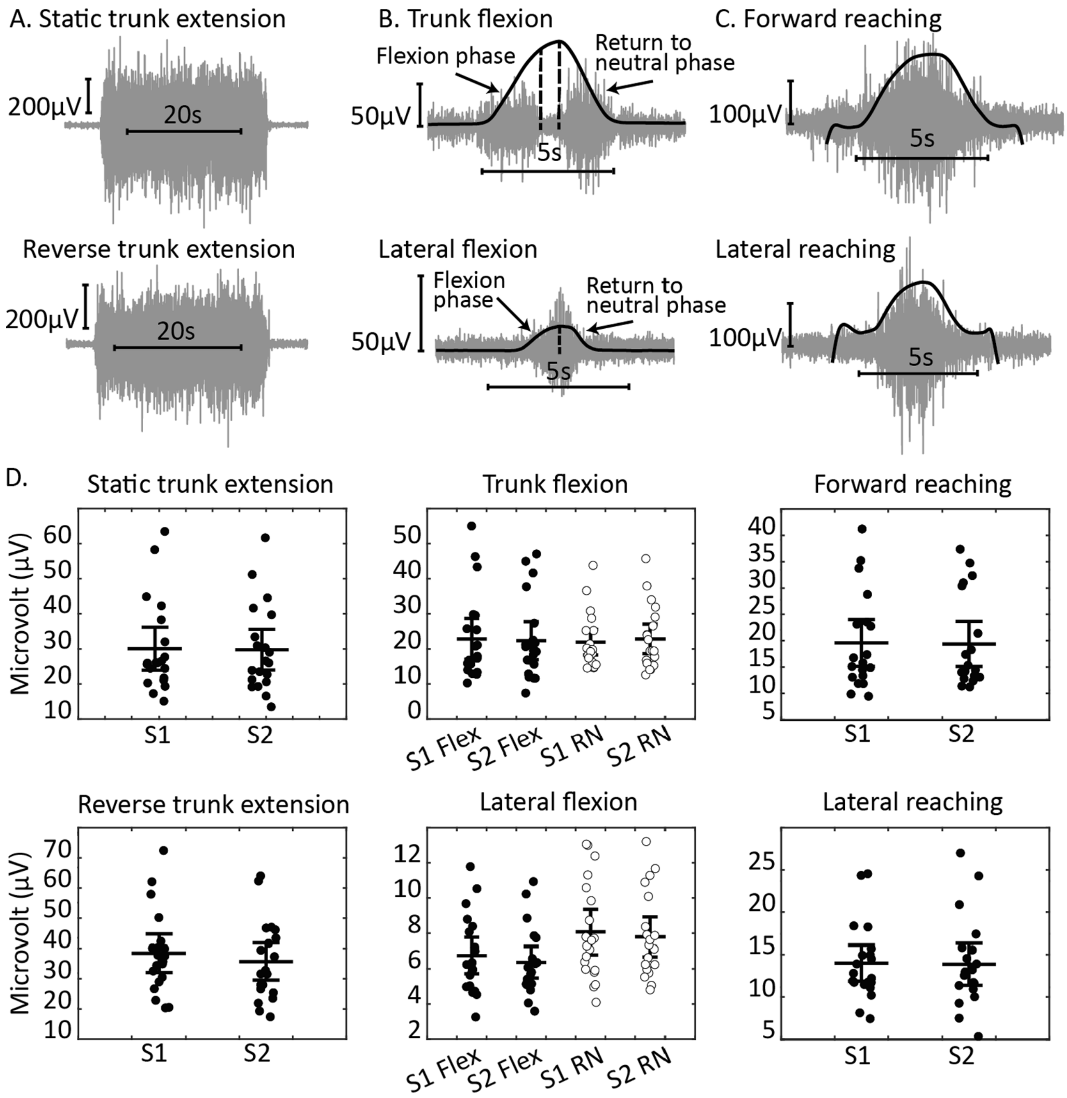

Fig. 2. Raw EMG traces and spread of absolute RMS values. (A) Raw EMG traces from a representative participant during (A) static trunk extension (top) and reverse trunk extension (bottom). (B) Trunk flexion (top) and lateral flexion (bottom). Both dynamic tasks are separated into a flexion phase, and a return to neutral phase (i.e., extension) where participants returned to zero degrees of trunk flexion. Dashed lines represent the points of separation between the flexion phase and return to neutral phase during trunk flexion tasks. (C) Forward reaching (top) and lateral reaching (bottom). Black lines represent movements of the trunk during trunk flexion and lateral flexion and movements of the wrist during multidirectional reaching tasks. (D) Amplitudes of RMS EMG of individual participants. Results from left and right thoracic erector spinae (ES) are averaged for bilateral tasks. For unilateral tasks (i.e., lateral reaching and lateral flexion), results from the thoracic ES contralateral to each direction were averaged, e.g., right thoracic ES from left lateral reaching averaged with left thoracic ES from right lateral reaching. μV, microvolt; S1, session 1; S2, session 2; Flex, flexion phase; RN, return to neutral phase.

reliability were found for the x-axis barycentre (ICC: 0.57) and y-axis barycentre (ICC: 0.87), respectively. In addition, reliability of entropy was poor in forward reaching (ICC: 0.21) and good in lateral reaching (ICC: 0.76); SEM values remained low, ranging from 0.11 to 0.14 A.U. (Table 2).

4. Discussion

Our results show good-to-excellent intra-session reliability of HDEMG-derived measures obtained from the thoracic ES in all tasks. Inter-session reliability varied based on the task and was higher for most of the HDEMG parameters of static tasks than in dynamic tasks or functional reaching tasks. Overall, the findings suggest that RMS and MNF extracted from HDEMG are reliable in assessing characteristics of the activity of thoracic ES during goal-directed movements of the trunk as well as functional movements of the trunk, where the trunk muscles may not act as the prime mover. However, the measures of the barycentre and entropy demonstrate task-dependent reliability.

4.1. Reliability of spatial activity of the thoracic ES in static and dynamic movements of the trunk

HDEMG has been applied to evaluate the spatial distribution of paraspinal muscles during static and dynamic movements of the trunk in healthy adults and in clinical populations (Abboud et al., 2016; Abboud et al., 2014; Arvanitidis et al., 2021; Falla & Gallina, 2020). A previous study assessed the barycentre derived from HDEMG of lumbar paraspinal muscles during a lower back fatigue task (i.e., Sorensen test) and found high reliability between the two sessions (Abboud et al., 2015). Our results confirm the previous findings and show that the barycentre of the thoracic ES is reliable during static trunk extension and reverse trunk extension performed on separate days. This indicates that HDEMG provides reliable measurements for static contractions of the trunk muscles.

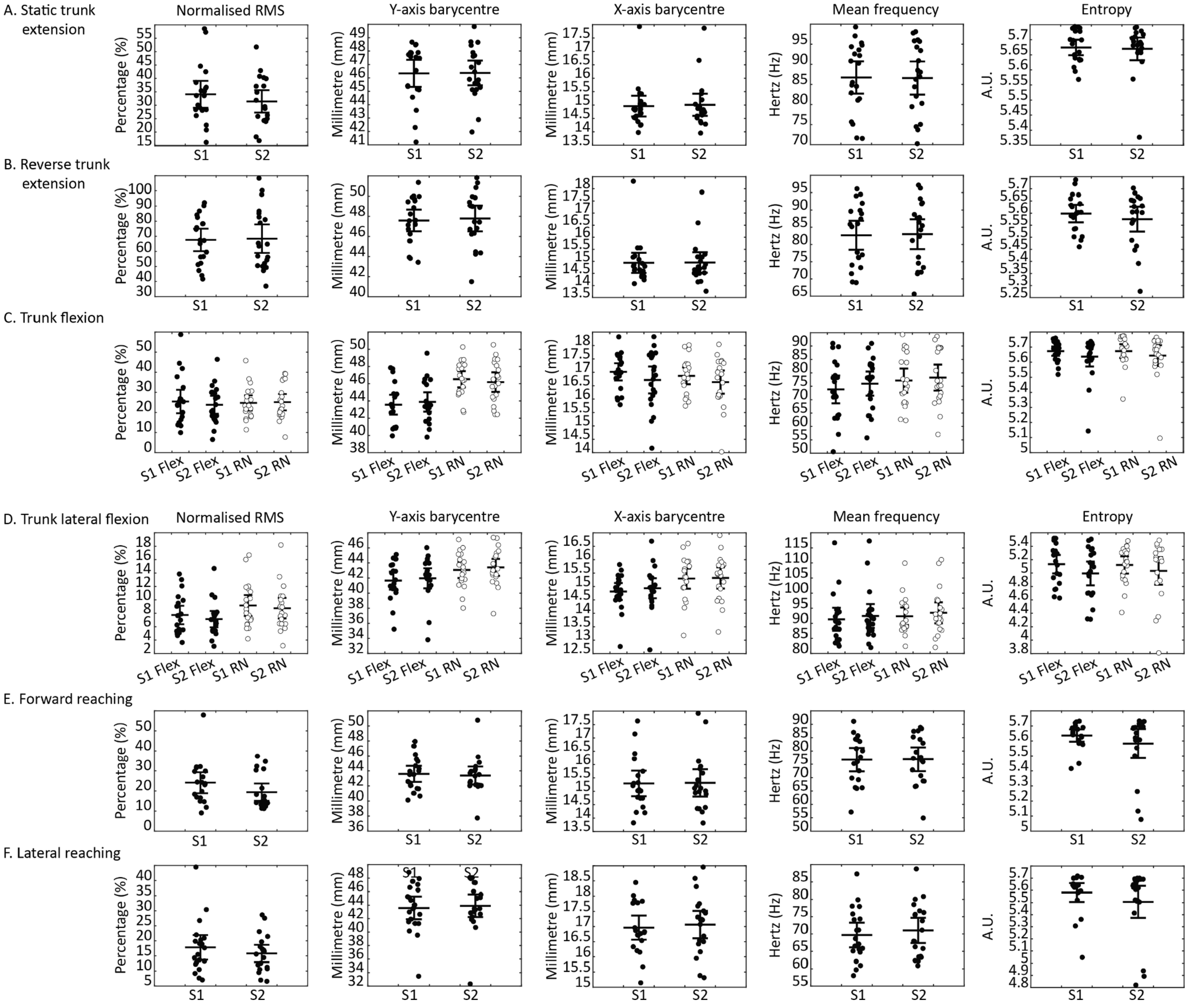

Fig. 3. Spread of values of normalised RMS, mean frequency, barycentre, and entropy. Individual results obtained from static tasks (A,B), goal-directed voluntary tasks (C, D), and functional reaching tasks (E,F). Wider horizontal lines depict the mean while smaller horizontal lines on the whiskers' end represent the 95% confidence interval. Results from left and right thoracic ES are averaged for bilateral tasks. For unilateral tasks (i.e., lateral reaching and lateral flexion), results from the thoracic ES contralateral to each direction were averaged, e.g., right thoracic ES from left lateral reaching averaged with left thoracic ES from right lateral reaching. S1, session 1; S2, session 2; Flex, flexion phase; RN, return to neutral phase; A.U., arbitrary unit.

Trunk muscles are activated in goal-directed voluntary movements, such as forward flexion, extension, and lateral flexion. We showed moderate-to-excellent inter-session reliability of the absolute RMS and MNF of the thoracic ES during both flexion and return to neutral phases of dynamic trunk flexion and lateral flexion. This aligns well with prior work reporting good reliability of bipolar EMG amplitude in the lumbar part of the ES muscles during a lifting task involving dynamic movements of the trunk (Brandt et al., 2017; Lariviere et al., 2000; Schinkel-Ivy et al., 2015). Interestingly, the reliability of the barycentre was influenced by direction of the movements in the dynamic tasks. For the trunk flexion task, the y-axis barycentre showed good reliability during both flexion and return to neutral phases, whereas reliability of the x-axis barycentre was poor during both phases of the movement. Conversely, for the trunk lateral flexion task, reliability of the x-axis barycentre was better than that of the y-axis barycentre. Trunk flexion–extension in standing primarily activates the trunk extensors (McGorry et al., 2001), i.e., the ES, and occurs in the sagittal plane, thereby influencing the y-axis barycentre, while trunk lateral flexion activates multiple muscles on the side of the body and occurs in the frontal plane, which is more likely to affect the x-axis barycentre. This may cause the reliability of the barycentre to be different between movements. In addition, the same individual may employ different movement strategies between sessions. This may affect regional activity of the ES muscles, causing a lower reliability of the barycentre and entropy.

Many activities of daily living require coordination of upper limbs and the trunk. For example, trunk muscles are activated to assist the arms in completing reaching movements (Caronni et al., 2013; Massion, 1992) as well as to maintain the centre of mass of the body to be within the base of support during movements of the arms (Chiou et al., 2016; Hodges & Richardson, 1999). Here we evaluated the reliability of spatial characteristics of EMG in the thoracic paraspinal muscles during forward and lateral reaching. Inter-session reliability of absolute RMS and MNF of the thoracic ES was good-to-excellent for the reaching tasks. Inter-session reliability of the barycentre was depended on the reaching direction. In the reaching tasks, trunk muscles have two roles: assisting the arms to reach to the target direction and maintaining stability of the body but are not non-prime movers in either of the roles. On the

Table 1
Intra-session reliability of HDEMG parameters and tasks.

Parameter	Stats	Static movement		Dynamic trunk flexion		Dynamic lateral trunk flexion		Reaching	
		Trunk extension	Reverse trunk extension	Flexion phase	Return to neutral phase	Flexion phase	Return to neutral phase	Forward	Lateral
Absolute RMS	ICC	0.99	0.95	0.94	0.95	0.91	0.93	0.98	0.95
	SEM	1.54	3.00	2.78	1.76	0.72	0.77	1.28	0.96
	CoV %	4.26	7.20	12.22	7.39	7.65	7.7	5.16	7.04
Normalised RMS	ICC	0.97	0.91	0.89	0.92	0.94	0.93	0.97	0.96
	SEM	1.65	5.56	3.54	2.28	0.72	0.84	1.67	1.46
	CoV %	4.26	7.20	12.22	7.39	7.65	7.7	5.16	7.04
X-axis barycentre	ICC	0.98	0.99	0.95	0.97	0.88	0.89	0.99	0.94
	SEM	0.13	0.07	0.20	0.14	0.36	0.32	0.11	0.25
	CoV %	0.69	0.38	0.87	0.73	1.66	1.49	0.66	1.38
Y-axis barycentre	ICC	0.94	0.97	0.92	0.92	0.88	0.90	0.93	0.91
	SEM	0.54	0.41	0.71	0.64	1.18	1.19	0.61	1.05
	CoV %	0.88	0.71	1.36	1.19	2.42	2.10	1.20	1.76
Mean frequency	ICC	0.98	0.98	0.96	0.97	0.88	0.91	0.98	0.97
	SEM	1.11	1.11	1.96	1.93	3.30	2.92	1.45	1.39
	CoV %	1.32	1.44	2.25	2.00	2.67	2.64	1.58	1.82
Entropy	ICC	0.94	0.91	0.87	0.89	0.81	0.79	0.94	0.80
	SEM	0.02	0.03	0.04	0.04	0.21	0.20	0.03	0.07
	CoV %	0.22	0.36	0.43	0.41	3.27	3.08	0.43	0.87

RMS, root mean square; ICC, intraclass correlation coefficient; SEM, standard error of measurement; CoV%, normalised coefficient of variation.

Table 2
Inter-session reliability of HDEMG parameters and tasks.

Parameter	Stats	Static movement		Dynamic trunk flexion		Dynamic lateral trunk flexion		Reaching	
		Trunk extension	Reverse trunk extension	Flexion phase	Return to neutral phase	Flexion phase	Return to neutral phase	Forward	Lateral
Absolute RMS	ICC	0.98	0.88	0.91	0.92	0.85	0.89	0.93	0.86
	SEM	1.84	4.27	3.74	2.39	0.91	1.03	2.39	1.88
	CoV %	5.07	10.00	14.20	10.17	10.19	8.97	12.43	10.71
Normalised RMS	ICC	0.59	0.21	0.73	0.87	0.71	0.74	0.59	0.42
	SEM	6.27	16.32	5.83	3.08	1.68	2.02	5.71	6.06
	CoV %	10.14	16.18	16.81	10.09	14.27	16.15	14.89	16.78
X-axis barycentre	ICC	0.90	0.90	0.49	0.29	0.65	0.50	0.94	0.57
	SEM	0.30	0.29	0.63	0.68	0.56	0.68	0.26	0.69
	CoV %	1.23	1.38	2.18	2.01	2.52	2.79	1.32	3.58
Y-axis barycentre	ICC	0.84	0.88	0.76	0.77	0.53	0.23	0.60	0.87
	SEM	0.86	0.89	1.20	1.06	2.39	3.28	1.49	1.19
	CoV %	1.34	1.48	2.13	1.82	3.93	4.12	3.01	2.31
Mean frequency	ICC	0.98	0.96	0.88	0.93	0.78	0.66	0.92	0.88
	SEM	1.32	1.78	3.38	2.57	4.74	5.62	2.63	2.76
	CoV %	1.32	1.68	3.02	2.49	3.17	4.00	2.22	3.04
Entropy	ICC	0.64	0.66	0.28	0.23	0.49	0.51	0.21	0.76
	SEM	0.04	0.05	0.10	0.11	0.32	0.31	0.14	0.11
	CoV %	0.53	0.76	1.11	1.17	4.91	4.55	1.81	1.90

RMS, root mean square; ICC, intraclass correlation coefficient; SEM, standard error of measurement; CoV%, normalised coefficient of variation.

contrary, trunk muscles are the prime movers in the goal-directed voluntary movements of the trunk. Our results suggest task-specific influences on EMG reliability of trunk muscles.

4.2. Reliability of absolute and normalised HDEMG during static and dynamic movements of the trunk

Normalisation of EMG is recommended to reduce variations within and between participants (Burden, 2010; McLean et al., 2003; Meskers et al., 2004). However, several studies reported the reliability being lower for the normalised EMG than for the absolute EMG in shoulder (Andersen et al., 2014; Michener et al., 2016) and trunk (Brandt et al., 2017; Schinkel-Ivy et al., 2015) muscles. Our findings are in line with previous reliability studies using conventional bipolar EMG, showing lower inter-session relative reliability of normalised RMS during static and dynamic tasks. The absolute reliability was also lower in the normalised RMS compared to the absolute RMS as seen by higher SEM values. It is common that MVCs of trunk muscles are performed with resistance manually applied to the participants (Brandt et al., 2017; Schinkel-Ivy et al., 2015), as performed in this study. However, techniques of the assessor and the participants to generate reliable MVCs between the two sessions potentially increase the variations of EMG recordings and therefore may explain the differences in reliability between the absolute and normalised RMS. Our results suggest that for repeated measures of the paraspinal muscles using HDEMG in healthy young participants, absolute RMS variables are more reliable than normalised RMS variables. Future work should consider a comparison of the reliability between bipolar EMG and HDEMG for the ES muscles for recommended use of the two modalities.

4.3. Limitations

There are limitations of the study which should be considered. Firstly, levels of thoracic ES muscle activity were low in the dynamic trunk flexion and lateral flexion tasks, especially during the flexion phase, despite a weight equivalent to 5 % of the individual's body mass being used to increase thoracic ES muscle activity. This may potentially influence the reliability of the displacement of the centroid in x- and y-axis, which is calculated from a topographical representation of absolute RMS, since a low level of EMG amplitude can cause the EMG signals to be less reliable (Potvin & Bent, 1997). Secondly, repositioning electrodes across sessions can be challenging and may consequently influence reliability results. However, inter-session reliability of the barycentre in static tasks was considered good. Based on this, the lower reliability observed in dynamic and functional tasks are likely attributable to the direction of the movement and motor strategies used by the individuals. Nevertheless, inter-session reliability remains acceptable for most HDEMG parameters. Thirdly, the recordings were performed between T8 and T12 levels of the ES. It warrants further investigation on the reliability of HDEMG-derived parameters from other regions of the trunk extensors at different spinal levels. Finally, our participants were young and healthy with normal BMIs. Whether the same reliability can be obtained from a different population, such as older adults and people with obesity, remains to be established.

5. Conclusions

Several variables extracted from HDEMG can reliably measure activity of bilateral thoracic ES muscles in healthy individuals between sessions for both goal-directed voluntary movements of the trunk and in functional reaching where the trunk muscles are not a prime mover. Specifically, inter-session reliability of absolute RMS and MNF was moderate-to-excellent across tasks, while the highest reliability findings are reported for static tasks compared to dynamic tasks and functional tasks. For the dynamic tasks, reliability of the barycentre may be influenced by the direction of the movements. Interestingly, reliability between sessions was higher for the absolute RMS than for the normalised RMS in all tasks, however, both parameters showed good-to-excellent intra-session reliability.

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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