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Highlights

• Analysis of trunk electromyograms show compared to younger adults older adults have. • Higher trunk Q2 muscle activation but differences were not systematic for all muscles. • Less temporal adjustment in abdominal site activation to changing external loads. • Altered temporal synergies among specific abdominal and back extensor sites. • Sustained activity and altered synergies imply dynamic spinal load pattern changes with age.

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Age-related changes in trunk neuromuscular activation patterns during a controlled functional transfer task include amplitude and temporal synergies

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A B S T R A C T

While healthy aging is associated with physiological changes that can impair control of trunk motion, few studies examine how spinal muscle responses change with increasing age. This study examined whether older (over 65 years) compared to younger (20–45 years) adults had higher overall amplitude and altered temporal recruitment patterns of trunk musculature when performing a functional transfer task. Surface electromyograms from twelve bilateral trunk muscle (24) sites were analyzed using principal component analysis, extracting amplitude and temporal features (PCs) from electromyographic waveforms. Two PCs explained 96% of the waveform variance. Three factor ANOVA models tested main effects (group, muscle and reach) and interactions for PC scores. Significant ($p < .0125$) group interactions were found for all PC scores. Post hoc analysis revealed that relative to younger adults, older adults recruited higher agonist and antagonistic activity, demonstrated continuous activation levels in specific muscle sites despite changing external moments, and had altered temporal synergies within abdominal and back musculature. In summary both older and younger adults recruit highly organized activation patterns in response to changing external moments. Differences in temporal trunk musculature recruitment patterns suggest that older adults experience different dynamic

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spinal stiffness and loading compared to younger adults during a functional lifting task.

1. Introduction

Industrialized nations worldwide are experiencing an aging demographic, with projections that by 2050, one in three individuals will exceed an age of 60 years (United Nations, 2011). While a majority of older adults live and complete activities of daily living independently (Scott, Pearce, & Pengelly, 2005), they have an increased risk of experiencing both falls (Pijnappels, Delbaere, Sturnieks, & Lord, 2010; Scott et al., 2005) and low back pain (Gourmelen et al., 2007; Plouvier, Gourmelen, Chastang, Lanoe, & Leclerc, 2011). The falls literature has focused on lower extremity joint function (Gillespie et al., 2012) although the ability to control trunk motion during both voluntary and unexpected perturbations has implications for maintaining dynamic stability during functional tasks (Doi et al., 2013; Grabiner et al., 2008). The spine is inherently unstable with links made between spinal instability and spinal injury (Cholewicki, Panjabi, & Khachatryan, 1997; Panjabi, 2003). Spine instability is partially explained by its osteoligamentous structures (ligaments, bones, discs, joint capsules, etc.) which contribute to passive stiffness only at end range of motion (Panjabi, 2003). Thus when in neutral spinal postures active stiffness through the interactions among the active force generation (skeletal muscles) and neural control (central and peripheral nervous system) components are needed to maintain stability (Cholewicki et al., 1997; McGill, Grenier, Kavcic, & Cholewicki, 2003). Alterations in one component requires compensation from the others, and this is particularly evident during dynamic tasks where the time varying recruitment of trunk musculature can change dynamic joint stability by altering active spinal stiffness (McGill et al., 2003; Panjabi, 2006).

Relevant to this study is that each component can be modified with increased age including decreases in joint space (de Schepper et al., 2010), muscle strength (Hasue, Fujiwara, & Kikuchi, 1980), contractile speed (D'Antona, Pellegrino, Carlizzi, & Bottinelli, 2007), action potential velocity (Rivner, Swift, & Malik, 2001), joint position sense (Goldberg, Hernandez, & Alexander, 2005), and changes in central nervous system recruitment (Van Impe, Coxon, Goble, Wenderoth, & Swinnen, 2011). These alterations can challenge spinal motion/stability control in older adults mainly in a neutral position where joint space narrowing results in increased neutral zone motion of the vertebra (Sengupta & Fan, 2014) and for dynamic tasks that require neuromuscular integration (de Freitas, Knight, & Barela, 2010). The literature supports an association between trunk function and both balance and fall risk (Davidson, Madigan, Nussbaum, & Wojcik, 2009; Doi et al., 2013; Goldberg et al., 2005; Grabiner et al., 2008; Hicks et al., 2005a; Kell & Bhambhani, 2006) as well older adults with low back disorders have an increased risk of falls (Leveille et al., 2010). Q4

Differences in trunk kinematics and kinetics variables were found between older and younger adults (Burgess, Hillier, Keogh, Kollmitzer, & Oddsson, 2009; Grabiner et al., 2008; McGill, Yingling, & Peach, 1999; Van Emmerik, McDermott, Haddad, & Van Wegen, 2005), but there is limited research comparing trunk muscle responses between older and younger adults. Since motion is partially controlled by the time varying tension generated by multiple trunk muscles (coordination) (Cholewicki et al., 1997; Rashedi, Khalaf, Nassajian, Nasseroleslami, & Parnianpour, 2010), alterations in muscle responses with age would be expected. In general older adults were found to have: (i) increased overall activation of both agonist (Asaka & Wang, 2008; Kuo, Kao, Chen, & Hong, 2011) and antagonist muscles (Asaka & Wang, 2008; McGill et al., 1999), and (ii) delayed onset time to voluntary and involuntary trunk motion (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; de Freitas et al., 2010; Hwang, Lee, Park, & Kwon, 2008). Two methodological issues exists that limit our understanding of the age-related differences in synergies among the comprehensive trunk musculature and their responsiveness to dynamic forces normally found in activities of daily living. First, most studies only characterize a few (2–4) trunk muscle sites (Allum et al., 2002; Asaka & Wang, 2008; de Freitas et al.,

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2010; Kuo et al., 2011) even though the trunk consists of multiple muscles, many with multiple fiber orientations and unique mechanical advantages (Dumas, Poulin, Roy, Gagnon, & Jovanovic, 1991; Granata & Marras, 2000; Kavcic, Grenier, & McGill, 2004; Rashedi et al., 2010; Stokes, Gardner-Morse, & Henry, 2011) and innervations (Urquhart, Barker, Hodges, Story, & Briggs, 2005). Second, discrete parameters such as onsets/offsets (Allum et al., 2002; Brown, Mills, & Baker, 1994; Hwang et al., 2008) or peak/average muscle activation amplitudes that do not capture dynamic responses throughout the entire movement (Kuo et al., 2011; McGill et al., 1999) are reported.

A study that examined 12 abdominal muscle sites during a supine dynamic leg-loading exercise task, showed that relative to younger adults, older adults had altered temporal recruitment patterns including a more sustained activation pattern whereas younger adults responded to the changing external moments (Hubley-Kozey, Hanada, Gordon, Kozey, & McKeon, 2009). Whether similar alterations would be found during more functional tasks performed in upright standing postures where spinal stability and motion control are challenged was the focus of the present study. Previous work reported unique activation patterns among abdominal and back muscle sites for healthy young adults during dynamic experimental tasks performed in upright standing postures consistent with responses to changing external moments (Hubley-Kozey, Butler, & Kozey, 2012; Hubley-Kozey, Moreside, & Quirk, 2013). Differences in temporal patterns were reported between sexes (Hubley-Kozey et al., 2012) and for those deemed recovered from a low back injury (Hubley-Kozey et al., 2013) relative to healthy controls. To better understand aging effects on spinal stability and motion control for more functional tasks, we conducted a comprehensive study to examine trunk muscle coordination and synergies during a dynamic task performed in upright standing postures. Collectively the literature supports that trunk muscle function can impact risk of falls and low back disorders in older adult, hence the motivation for the present work.

The purpose of this study was (i) to test if healthy older adults have different trunk muscle amplitude and temporal activation patterns compared to healthy younger adults during a controlled dynamic functional lift and replace task and (ii) to determine if differences were altered by task intensity. We hypothesized that compared to younger adults older adults would have higher overall activation of all muscle sites, and altered temporal patterns including more sustained activity throughout the task and altered temporal synergies reflecting changes in passive stiffness, muscle strength and central and peripheral control associated with aging.

2. Methods

2.1. Participants

Participants, recruited from the general population via advertisements and electronic notices, signed an informed consent approved by the Institution Ethics Review Board. Seventeen older adults (65+ years old) were matched with younger adults (20–45 years old) selected from a larger group of 60 participants based on sex, mass (±3 kg), and height (±7 cm). 26 younger adults fit these criteria with 7 older adults having 2–3 potential matches. Exclusion criteria for both groups included self-reported cardiovascular, neurological, cognitive, or musculoskeletal conditions, and a low back injury within the last year that required medical attention, or limited daily function.

2.2. Test procedure

A telephone health screen was conducted, and then confirmed during testing. Participants attended an initial session to familiarize them with the protocol and experiment task. Anthropometric data, number of weekly aerobic activity lasting over 30 min (Gilleard & Brown, 1994), number of abdominal training sessions per week were recorded and abdominal function ability (Kendall & McCreary, 1983) was tested. Older adults completed Mini Mental Status Exam and were included if their score exceeded 27/30 (Folstein, Folstein, & McHugh, 1975).

Testing took place within two weeks of the initial session. All participants performed a controlled right-to-left transfer task, using a 2.9 kg mass (Hubley-Kozey et al., 2012). Participants stood with

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their body midline aligned with the center of a standing elbow height adjusted table. They performed three trials of a standardized lift, transfer and replace task within a standardized 5 s count: lift on 1, midline on 3, replace on 5 (Fig. 1a–c). Time to complete each phase and total time were calculated from the event data. To minimize trunk motion, participants were provided with tactile feedback from a sensor placed at the mid thoracic spine during upright standing in their starting position (Butler, Hubley-Kozey, & Kozey, 2010). If timing or motion deviations were detected (either visually by the tester or from the recorded event and motion traces), the trial was repeated. Both were later quantified as described below to confirm observations. These constraints resulted in a dynamic task that produced continuously changing flexion and lateral flexion moments around the spine, created primarily by the external load (Fig. 1d). To increase task intensity participants performed the task in two conditions; normal reach and maximum reach where participants maintained an elbow position of 90° flexion or full extension respectively (Butler, Hubley-Kozey, & Kozey, 2009).

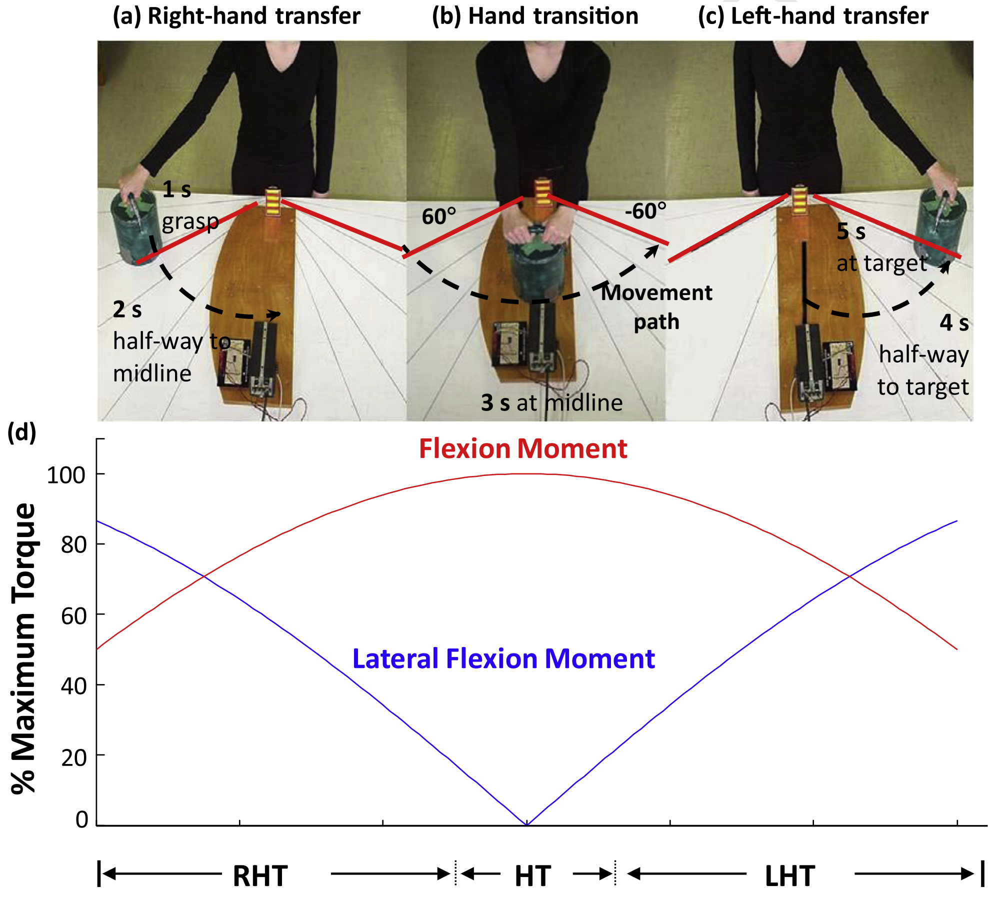

Fig. 1. Experimental set-up and subject posture showing (a) starting position (lift at 60° to their body midline using their right hand) (b) load transfer when it passed the mid-point of the body with height lifted approximately 4–5 cm above the table surface with both hands (c) using the left hand the ending position (replace at −60° from the body midline). Panel (d) includes the flexion and lateral flexion moment paths as the load is transferred from one side of the body to the other. Pressure sensors on the bottom of a 2.9 kg mass indicated time of lift off and replace; an optoelectric light sensor indicated when the load crossed midline. These events defined 3 phases: right hand transfer (RHT), hand transition (HT) and left hand transfer (LHT). Reprinted from: Human Movement Science, 31, Hubley-Kozey, C.K.; Butler, H.L; Kozey J.W., pp. 867, Copyright 2012, with permission from Elsevier.

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2.3. Normalization procedure

Each participant performed two trials of eight maximum voluntary isometric exercises for EMG amplitude normalization (percentage of maximum voluntary effort). Participants maintained a constant maximal effort for 3 s with a 2-min rest between trials. These exercises have been found feasible for older adults (Hanada, Hubley-Kozey, McKeon, & Gordon, 2008) and included a resisted: sit-up, lateral bend (left/right), trunk extension, trunk extension with left/right rotation, and seated rotation (left/right) (Butler et al., 2010). A series of normalization tasks has been found superior to elicit maximum response in trunk muscles compared to a single maximum voluntary contraction exercise (Vera-Garcia, Moreside, & McGill, 2010).

2.4. EMG data acquisition and processing

Following standard skin preparation, surface electrodes (Ag/AgCl, 10 mm circular electrodes; Meditrace, Graphics Control Canada Ltd) were positioned in a bipolar configuration (inter electrode distance of 30 mm) along the fiber orientation of 12 bilateral muscle sites. Abdominal muscle sites included placement over upper (URA) and lower rectus abdominis (LRA), internal oblique (IO) and three sites over external oblique (EO1–3), representing the anterior, lateral and posterior fibers of this muscle, respectively. Back extensor sites included erector spinae at the lumbar level 1 (L1) and 3 (L3), positioned 3 cm and 6 cm lateral to the midline to represent the longissimus (L13, L33) and iliocostalis (L16, L36) sites; as well as over quadratus lumborum (L48) and multifidus (L52). Specific anatomical landmarks used for these electrode sites and supporting literature have been previously described (Butler et al., 2010). Electrode placements were validated using a series of manual muscle tests (Kendall & McCreary, 1983; Vezina & Hubley-Kozey, 2000) with slight changes in placement to accommodate individual anthropometry when necessary.

EMG signals were pre-amplified (500×) and further amplified using three AMT-8 EMG systems (band pass 10–1000 Hz; CMRR = 115 db, input impedance 10 GΩ; Bortec Inc., Calgary, Alberta). EMG signals and event markers were digitized at 2000 Hz using a 16 bit resolution analog-to-digital conversion board (PCI-6033E, National Instruments, Austin, Texas) and Labview™ software (version 7), then stored for processing.

Custom Matlab™ code (Math Works, Natick, Massachusetts) corrected EMG signals for subject bias, calculated the amplitude at the skin level using the calibration constant, high pass filtered (30 Hz) to remove electrocardiogram artifact (Butler, Newell, Hubley-Kozey, & Kozey, 2009) and applied an inverse fast-Fourier filter to remove electromagnetic sensor noise. Raw corrected signals were full wave rectified then low passed filtered at 6 Hz using a second order recursive Butterworth filter to produce a linear envelope. Signals were amplitude normalized to the maximum voltage regardless of the exercise recorded from a 500 ms moving average amplitude recorded from each muscle site during the normalization exercises (Vezina & Hubley-Kozey, 2000), and time was normalized from lift off (0%) to replace (100%) using a quadratic interpolation algorithm.

EMG ensemble average waveforms for each participant (43), muscle (24) and condition (2) (2064 × 101) were entered into a Principal Component Analysis (PCA) model (Hubley-Kozey et al., 2009, 2012; Jackson, 2003) to capture the amplitude and temporal characteristics from the comprehensive set of abdominal and back extensor EMG waveforms. Briefly, eigenvector decomposition was performed on the covariance matrix of the original waveform matrix, resulting in a set of principal components (PCs) explaining patterns of variation within the measured EMG waveforms. For each waveform, a PC score which is a weighting coefficient of how much variance in the original waveform features are capture by each PC. The PC scores are included in statistical comparison of EMG waveform features with waveforms similar in shape and amplitude having similar PC scores (Ivanenko, Poppele, & Lacquaniti, 2004). PC scores explaining over 90% of the total waveform variance were included in statistical analyses. In addition, sample ensemble average waveforms were calculated for each group, for each muscle and each condition (Winter & Yack, 1987).

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2.5. Motion capture data collection and processing

An electromagnetic Flock of Birds™ (FOB) Motion Capture system (Ascension Technology Inc., Burlington, Vermont) recorded the 3D angular motion of the trunk and pelvis throughout the task with respect to a global coordinate system (Silfies, Squillante, Maurer, Westcott, & Karduna, 2005). One sensor was placed superior to the left anterior superior iliac crest, the second over the T8 spinous process. Participants were positioned such that sensor motion corresponded with anatomical planes of motion (Axial Rotation (AR), Flexion/Extension (FE), and Lateral Bend (LB)). Motion data and event markers were sampled at 50 Hz using a 12 bit analog-to-digital board (National Instruments, DAQPad-6020E) and Labview, and then stored for post processing. Angular motion data were low-pass filtered using a 2 Hz second order recursive Butterworth Filter. Using event markers, angular motion data were windowed for the entire movement and the maximum angular displacements were calculated for each sensor in all 3 planes.

2.6. Statistical analysis

Student *t*-test or Fishers exacts test were used to test parametric and non-parametric demographic and anthropometric variables. Angular displacement data were compared using a mixed model analysis of variance (ANOVA) (Group * Reach). Differences in PC scores for the abdominal and back muscle sites were tested in separate mixed model ANOVAs (Group * Reach * Muscle). Tukey simultaneous post hoc comparisons were performed on significant effects. Normality was confirmed using a Kolmogorov–Smirnov test, with non-normal data being transformed using a Johnson Transformation. Statistical analyses were performed in Minitab (Minitab Inc, State Collage, PA, version 16), with $\alpha = 0.0125$ (.05/4) for PC scores, and $\alpha = 0.008$ (.05/6) for angular displacement data.

3. Results

3.1. Participant demographics and performance: Timing and kinematic variables

Groups were similar for descriptive characteristics except older adults had a significantly greater waist circumference (approximately 3 cm) compared to younger adults (Table 1). The mean total time to complete the task was 3.9 ± 0.4 s with total time and time to complete each phase of the lift and replace task similar between groups and conditions ($p > .05$). Mean overall maximum trunk and pelvis motion ranged from 0.5° to 2.2° (Table 2) for both groups and all conditions. There was minimal variability for each measure, confirming that participants in both groups attempted to minimize motion. Significant ($p < .008$) main effect for maximum angular displacements are indicated in Table 2. Older adults had greater trunk motion than younger adults with the largest differences 0.8° for axial

Table 1
Descriptive statistics for participants in this study.

Comparison	Older adults	Younger adults
Participants (number)	17	26
Age (years)	67.8 (2.5)*	29.7 (7.3)
Sex (% male)	76	69
Mass (kg)	82.6 (15.0)	79.4 (13.0)
Height (cm)	171.7 (7.6)	173.4 (7.9)
BMI (kg/m^2)	27.9 (4.1)	26.2 (2.7)
Waist girth (cm)	94.9 (12.8)*	91.2 (13.2)
Aerobic training (sessions/week)	3.5 (3.1)	4.4 (3.8)
Abdominal Training (sessions/week)	1.4 (2.0)	1.7 (2.0)
Normal abdominal function (% complete)	82	88

Mean (SD).
* Significant difference ($p < .05$) between younger and older adults.

Table 2
Means and standard deviation for the motion data for older (Old) and younger (YNG) adults in normal (Norm) and maximum (Max) reach distances.

	Pelvis (°)			Trunk (°)		
	Lat. Flex	**Flex.-Ext.**	**Axial Rot.**	**Lat. Flex.**	**Flex.-Ext.**	**Axial Rot.**
YNG	0.8±0.6	1.0±0.8	1.8±1.5	0.7±0.7	0.5±0.5	1.1±0.7
Old	0.9±0.7	0.8±0.7	2.1±1.6	**1.2±1.3**	**1.0±1.1**	**1.9±1.5**
Norm	0.8±0.5	0.7±0.4	1.7±1.1	0.8±0.9	0.7±0.8	1.4±1.3
Max	0.9±0.7	1.2±0.9	2.2±1.9	1.0±1.1	0.8±0.9	1.5±1.2

Significant main effects included showing significant differences in Tukey HST Post hoc are denoted by: gray shading for reach = Maximum> normal, bold font for group Old> Young.

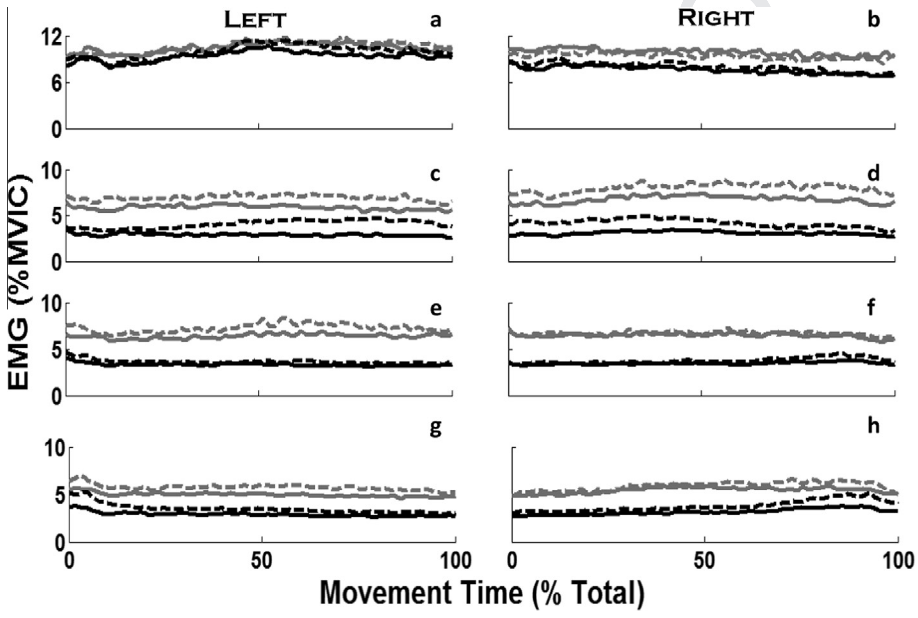

Fig. 2. Examples of ensemble average waveforms for specific abdominal sites. Black lines = younger adult group, gray lines = older adult group, solid lines = normal reach, dashed lines = maximum reach. Specific abdominal sites include left (L) and right (R) (a and b) L & RIO (c and d) L & REO1 (e and f) L & REO2 and (g and h) L & REO3.

rotation. This difference occurred primarily in the RHT phase with older adults having 3.2 ± 2.0° compared to 1.4 ± 0.9° of trunk axial motion for younger adults.

3.2. Qualitative EMG waveform analysis

Example ensemble average waveforms for the abdominal (Fig. 2) and back extensor (Fig. 3) muscles show qualitative differences between muscle sites, groups, and reach. Most abdominal and back extensor muscles had higher EMG activation amplitudes for older adults, but differences were not systematic among muscles (e.g. Fig. 2a versus d, f) or consistent throughout the task (Figs. 2a versus h or 3g versus e, f). Increasing reach distance resulted in higher activation in all back (Fig. 3) and some abdominal sites in both groups (Fig. 2c, d, g and h) but for specific sites these differences were dependent on phase (Fig. 3e versus b). PCA identified two dominant waveform features (PCs) captur-

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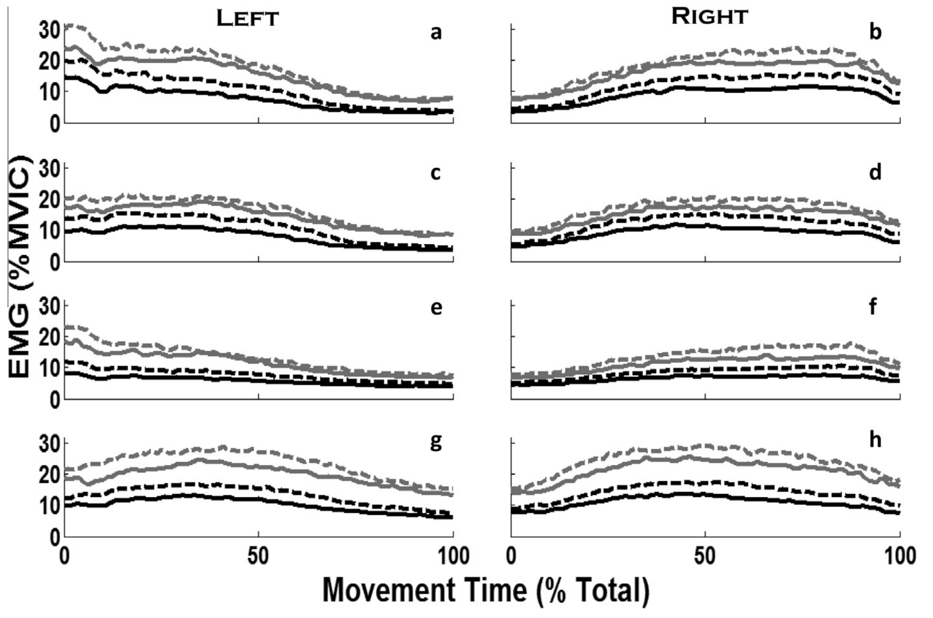

Fig. 3. Examples of ensemble average waveforms for specific back sites. Black lines = younger adult group, gray lines = older adult group, solid lines = normal reach, dashed lines = maximum reach. Specific back sites include left (L) and right (R) (a and b) L & RL16 (c and d) L & RL33 (e and f) L & RL48 and (g and h) L & RL52.

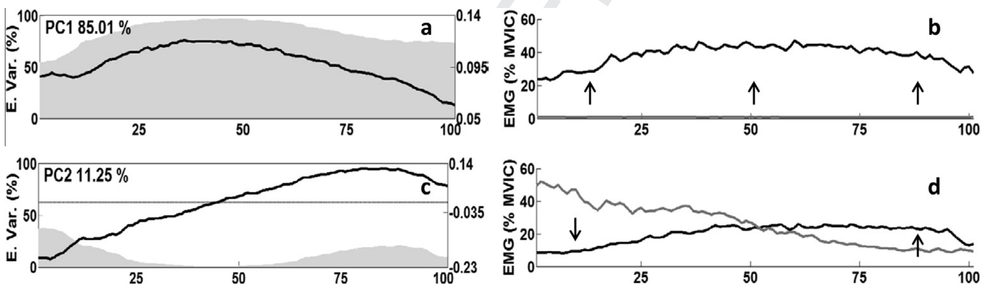

Fig. 4. For principal components (1–2) plots a and b show the principal component (black line), and explained variance relative to total movement time depicted by gray shading. Total explained variance for each principal component is shown in the top left corner of these plots. To aid with interpretation, for each principal component plots c and d show ensemble average waveforms of EMG activation patterns from the 5 highest (black line) and the 5 lowest (gray line) PC scores, along with black arrows indicating how the PC influences the shape of the high score.

ing over 96% of the total variance in the EMG waveforms. The two PCs and the high-low scores to assist with interpretation are illustrated in Fig. 4. Mean and standard deviations for PC scores are found in Tables 3 and 4 with the ANOVA results summarized in Table 5. Interaction plots for significant group interactions from Table 5 are found in Fig. 5. There were significant Group * Reach * Muscle interactions for both abdominal PC scores with significant Group * Reach and Group * Muscle interactions for PC1 and PC2 of the back extensor muscles respectively (Table 5).

3.3. Principal component 1

PC1 explained 85% of the total variance, capturing the overall magnitude and shape (Fig. 4a) including a gradual increase in muscle activity corresponding with the increasing flexion moment at hand

Table 3
Means and standard deviations of principal component scores (1–2) of abdominal sites for older (Old) and younger (YNG) adults in normal (Norm) and maximum (Max) reach.

PC	RLRA	LLRA	RURA	LURA	REO1	LEO1	REO2	LEO2	REO3	LEO3	RIO	LIO
1 Old norm	−45.1 ± 21^{cdef}	−38.9 ± 23^{cdf}	−41.6 ± 29^{cdf}	−37.8 ± 42^{cdf}	−**19.8 ± 51**^{f}	−**28.4 ± 42**^{f}	−26.1 ± 30^{f}	−19.7 ± 44^{f}	−35.3 ± 22^{cdf}	−36.1 ± 26^{cdf}	**4.6 ± 48**	**13.3 ± 45**
1 YNG norm	−65.6 ± 11^{cdef}	−65.2 ± 12^{cdef}	−65.2 ± 12^{cdef}	−64.1 ± 12^{cdef}	−56.5 ± 14^{f}	−58.4 ± 16^{f}	−53.1 ± 19^{f}	−54.4 ± 18^{f}	−56.3 ± 13^{f}	−58.5 ± 16^{f}	−**11.4 ± 33**	**1.9 ± 46**
1 Old max	−**45.3 ± 22**^{bcdef}	−**37.2 ± 23**^{bcdef}	−38.2 ± 32^{cdef}	−35.9 ± 42^{cdf}	−**7.3 ± 58**^{f}	−**18.0 ± 49**^{f}	−**20.9 ± 33**^{cf}	−**13.3 ± 56**^{f}	−28.8 ± 27^{cdf}	−30.0 ± 28^{cdf}	**6.1 ± 50**	**18.3 ± 48**
1 YNG max	−65.0 ± 11^{cdef}	−64.5 ± 12^{cdef}	−63.1 ± 14^{cdef}	−62.0 ± 14^{cdef}	−45.2 ± 18^{f}	−46.9 ± 18^{f}	−50.2 ± 19^{f}	−51.3 ± 19^{f}	−50.2 ± 15^{f}	−52.6 ± 19^{cf}	−**7.9 ± 39**	**6.3 ± 51**
2 Old norm	0.8 ± 1^{e}	1.3 ± 1	0.8 ± 1^{e}	1.1 ± 1	3.7 ± 6	1.4 ± 4	2.1 ± 6	3.4 ± 5	**4.2 ± 3**	**0.7 ± 2**	**0.6 ± 3**^{ce}	**6.7 ± 5**^{abcde}
2 YNG norm	0.6 ± 1^{e}	0.7 ± 1	0.4 ± 1^{e}	0.5 ± 1	1.2 ± 5^{e}	0.2 ± 4	2.1 ± 3	0.0 ± 2	**3.8 ± 3**	−**1.1 ± 3**	−**1.3 ± 4**^{cde}	**5.3 ± 7**^{abcde}
2 Old max	0.8 ± 1^{ce}	1.7 ± 1	1.1 ± 1^{ce}	1.7 ± 2	5.3 ± 11	2.6 ± 7	2.3 ± 7	4.3 ± 6^{e}	**5.7 ± 4**	**0.0 ± 2**	**0.5 ± 6**^{ce}	**9.8 ± 9**^{abcde}
2 YNG max	0.6 ± 1de	0.8 ± 1	0.4 ± 1de	0.9 ± 1^{e}	−**1.0 ± 8**^{de}	**5.3 ± 6**^{abde}	**3.6 ± 4**	−**0.5 ± 4**	**6.1 ± 5**	−**3.2 ± 6**	−**1.7 ± 5**^{de}	**7.9 ± 8**^{abcde}

Post hoc analysis indicating significant between muscle differences: for right and left side paired muscle sites within the same group and reach distance by bold lettering; and muscle differences between the same side muscles sites within a particular group and reach distance are represented by superscript a = LRA, b = URA, c = EO1, d = EO2, e = EO3, f = IO.

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Table 4
Means and standard deviations for principal component scores (1–2) of back sites for older (Old) and younger (YNG) adults in normal (Norm) and maximum (Max) reach.

PC	RL13	LL13	RL16	LL16	RL33	LL33	RL36	LL36	RL48	LL48	RL52	LL52
1 Norm	35.7±72 ^{f}	31.0±66 ^{f}	25.2±71 ^{af}	16.8±63 ^{f}	23.2±67 ^{af}	17.1±70 ^{af}	-2.6±64 ^{abcf}	-7.3±57 ^{abcf}	-5.2±51 ^{abcf}	-8.6±53 ^{abcf}	61.9±78	54.7±77
1 Max	72.1±86 ^{f}	66.9±78 ^{f}	**58.4±88** ^{af}	**49.1±73** ^{af}	**54.6±78** ^{af}	**46.1±78** ^{af}	**22.9±75** ^{abcf}	**15.2±64** ^{abcf}	17.8±69 ^{abcf}	12.5±62 ^{abcf}	**97.8±90**	**89.0±84**
2 Norm	**22.4±12** ^{b}	**-31.6±25** ^{b}	**30.0±23**	**-36.8±31**	**18.0±10** ^{ab}	**-21.6±16** ^{ab}	**20.2±19** ^{b}	**-22.3±20** ^{ab}	**15.9±17** ^{b}	**-17.0±23** ^{ab}	**14.6±17** ^{abcde}	**-8.0±11** ^{abcde}
2 Max	**31.4±15** ^{b}	**-44.2±32** ^{b}	**41.9±30**	**-53.7±42**	**25.2±11** ^{ab}	**-31.4±23** ^{ab}	**29.8±23** ^{ab}	**-33.0±29** ^{ab}	**24.6±26** ^{ab}	**-26.0±33** ^{abd}	**18.8±17** ^{abcde}	**-12.7±15** ^{abcde}
2 Old	**32.6±16** ^{b}	**-47.0±36** ^{b}	**43.2±30**	**-54.9±37**	**26.2±13** ^{ab}	**-27.8±17** ^{abde}	**31.2±31** ^{b}	**-34.3±33** ^{ab}	**28.9±33** ^{b}	**-33.7±41** ^{ab}	**24.9±21** ^{abd}	**-8.2±15** ^{abcde}
2 YNG	**23.1±11** ^{b}	**-31.9±22** ^{b}	**31.2±25**	**-39.0±35**	**18.6±9** ^{b}	**-25.7±22** ^{ab}	**20.9±12** ^{b}	**-23.3±18** ^{ab}	**14.6±8** ^{abcd}	**-13.5±11** ^{abcd}	**11.3±12** ^{abcde}	**-11.7±12** ^{abcd}

Post hoc analysis indicating significant between muscle differences for right and left side paired muscle sites within the same group and reach distance by bold lettering; and muscle differences between the same side muscles sites within a particular group and reach distance are represented by superscript a = L13, b = L16, c = L33, d = L36, e = L48, f = L52. Reach differences for muscle by reach interactions are indicated by gray shading.

Table 5
P-values for the main effects and interactions from the ANOVA test results for principal component scores with the main effects or interactions that were analyzed for post hoc differences indicated in bold.

Variable	Abdominals		Back extensors	
	PC1	PC2	PC1	PC2
Group	<0.001	0.009	0.001	0.812
Reach	<0.001	0.011	<0.001	0.066
Muscle	<0.001	<0.001	<0.001	<0.001
Group * reach	0.003	0.700	**<0.001**	0.103
Group * muscle	0.003	0.039	0.441	**<0.001**
Reach * muscle	<0.001	<0.001	**0.005**	**<0.001**
Group * reach * muscle	**<0.001**	**<0.001**	0.107	0.334

transition (HT), followed by a gradual decrease (Fig. 1d). High-low score curves show that high scores are associated with higher EMG amplitude (Fig. 4c). Post hoc analysis for the abdominal PC1 scores showed that for all muscles and both reaches, older adults had higher overall amplitudes than younger adults (Fig. 5a). Progressing from normal to maximum reach, overall muscle activation amplitudes increased for EO1 in both groups and for EO3 in the younger adults only (Figs. 5a and 3c, d, g and h). Differences among abdominal sites within groups and reach distances are found in Table 3 with IO higher than all other abdominal sites. Left versus right differences were found in both groups at both reach distances (higher left versus right PC1 scores) for IO sites (Table 3) with older adults having additional significant right/left differences i.e. 2 out of 6 and 4 out of 6 abdominal sites for normal and maximum reach respectively (Table 3).

Back site PC1 score post hoc analysis of the Group * Reach interaction showed that older adults had higher overall activation than younger adults for both reach distances, and a subtle increase in response to the increase in external moment (59 ± 80 to 91 ± 96 in old verses −5 ± 47 to 24 ± 56 in young adults when progressing from normal to maximum reach respectively) (Fig. 5b). Muscle * Reach post hoc analysis confirmed that all back sites increased overall activation (PC1) with increasing reach distance (Table 4), and that 4 of 6 back sites developed asymmetric activation (higher right PC1 scores compared to left) in maximum reach. Additional muscle differences are shown in Table 4.

3.4. Principal component 2

PC2 explained over 11% of the total variance capturing, a response to the lateral flexion moment as the mass was moved from right to left (Figs. 1d and 4b). Positive scores (high scores in Fig. 4d) corresponded with a muscle site having low initial activation relative to the gradual rise in activation that occurred at task termination. Negative scores were associated with the opposite pattern (low scores Fig. 4d).

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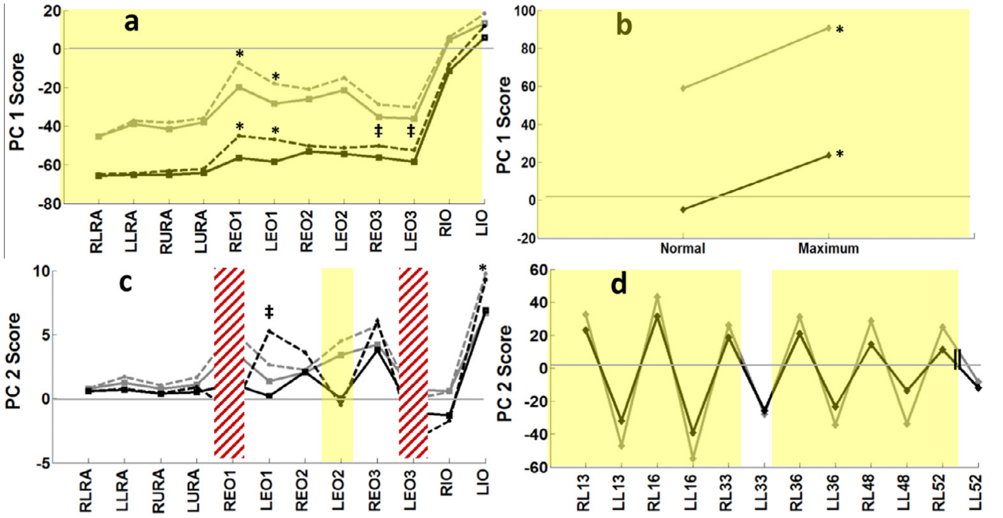

Fig. 5. Interaction plots for principal components scores 1 (a and b) and 2 (c and d) for the abdominal (a and c) and back (b and d) muscle sites. Common to all group interactions (a–d) older adults are illustrated by gray lines and younger adults are depicted by black lines. Common to all reach interactions (a and c) normal reach is represented by solid lines and maximum reach is depicted by dashed line reach. Significant group interactions are identified using: yellow shading for differences between groups in both reach distances, and red diagonal line shading for differences in maximum reach. Significant group differences in group by muscle interactions (b) are indicated by yellow shading and reach differences are indicated by ∗. For group by reach by muscle interactions (a and c) significant reach differences within a muscle site are indicated by: ∗ = for differences in both groups, and ‡ = for differences in younger adults only. To assist with interpretation of PC scores see corresponding High/Low score plots (Fig. 3b and d) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Post hoc differences for the abdominal sites showed that older adults had significantly different PC2 scores than younger adults for LEO2 in both reach distances (Fig. 2d), and for REO1 and LEO3 (Fig. 2a and e respectively) in maximum reach (Fig. 5c). Progression to maximum reach resulted in a significant increase in PC2 for the LIO in both groups (Fig. 2g), and the LEO1 in younger adults (Fig. 5c). While both groups had PC2 score differences between sides for IO and EO3, only younger adults had bilateral asymmetries for EO1 and EO2 in maximum reach Table 3. This illustrates a temporal synergy between EO1-IO (Fig. 6a), and EO2–EO3 (Fig. 6b) in the younger group only.

Group * Muscle interaction for the back sites showed that older adults had a higher magnitude PC2 score indicative of a greater relative response to the lateral flexor moment (higher absolute values for PC2 scores) for all back sites except LL33, and LL52 (Fig. 5d). The higher PC2 score magnitudes for L48 (Table 4) in older adults resulted in a temporal pattern similar to L36, which was not seen within the younger group (Fig. 6c). The Reach * Muscle post hoc and muscle differences are found in Table 4. Comparing back muscle sites for all groups and reach distances, L16 (more lateral) had the highest response to the lateral moment (Fig. 3a and b), and medial L52 (Fig. 3g and h) was the least responsive (Table 4) based on the magnitude of PC2 score.

4. Discussion

Two principal components captured the response of the trunk musculature to two predominant dynamic moments i.e. flexion (PC1) and lateral flexion (PC2). Consistent with previous findings for young adults (Hubley-Kozey et al., 2012, 2013) individual muscle sites had unique activation patterns in response to these changing moments, however there were both group and task intensity interactions, hence differences were not systematic. The results of this study confirmed our hypothesis, finding that despite similarities in demographics, kinematics, and timing characteristics, different

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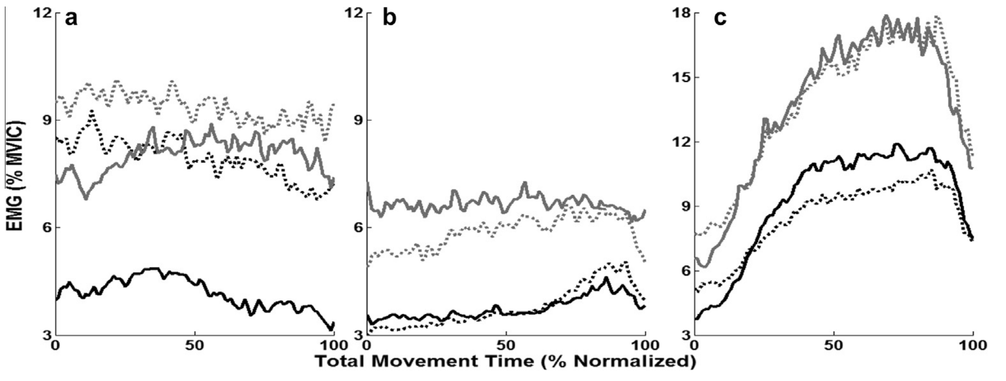

Fig. 6. Temporal waveform plots for older (gray) and younger (black) adults depicting the temporal synergy in younger adults in maximum reach shared by: (a) REO1 (solid) and RIO (dotted) and (b) REO2 (solid) and REO3 (dotted), and the temporal synergy in older adults for: (c) RL36 (solid) and RL48 (dotted).

amplitude and temporal responses were found between groups. In particular, compared to younger adults, older adults activated all muscle sites with higher relative amplitudes. Temporal differences were less systematic and varied by reach and/or muscle site thus modifying muscle synergies. The findings and their potential implications are discussed below.

4.1. Ability to selectively recruit trunk muscles to changing task demands

The significant muscle interactions found for PC scores for both abdominal and back muscle sites illustrate that the trunk musculature has unique responses to changing external moment generated by the lift, transfer and replace task (Butler et al., 2010; Hubley-Kozey et al., 2013, 2012). These flexion and lateral flexion responses support both experimental and theoretical models suggesting that different muscles are activated depending on their mechanical advantage (Arjmand, Gagnon, Plamondon, Shirazi-Adl, & Lariviere, 2010; Arjmand, Shirazi-Adl, & Parnianpour, 2008; Bogduk, Macintosh, & Pearcy, 1992; Brown & Potvin, 2005; Kavcic et al., 2004; Talebian, Mousavi, Olyaei, Sanjari, & Parnianpour, 2010; Vera Garcia, Elvira, Brown, & McGill, 2007; Vera-Garcia et al., 2010a; Ward et al., 2009). This ability to selectively recruit and scale trunk muscle activation patterns is an important mechanism for optimal joint loading (McGill et al., 2003), however, group interactions suggest that amplitude, and temporal recruitment differences were not systematic between groups and were specific to both reach and trunk muscle site.

4.2. Older adults have increased agonist and antagonist activation for trunk muscles

The higher overall activation for all muscles at both reach distances for older adults indicate a higher neural drive relative to maximum activation compared to younger participants (PC1 scores). This finding (Fig. 5b) is consistent with differences reported for older adults during unloaded movement tasks (Kuo et al., 2011). As the primary agonist, all back extensor sites increased their overall activation (PC1) with increasing task intensity (Table 4) consistent with previous reports (Butler et al., 2009, 2010). Therefore, group differences in overall neural drive of back extensor sites can in part be explained by increased relative task demands resulting from age-related strength loss (Hasue et al., 1980; Kubo, 1994; Sinaki, Nwaogwugwu, Phillips, & Mokri, 2001).

In contrast, the abdominal site alterations are less clear. Higher overall abdominal activation (PC1 scores) for older adults, or more antagonist activation (Fig. 5a), is unlikely influenced by increasing task intensity as neither group had a systematic activation increase in all abdominal sites with increasing reach distance (Fig. 5a). Higher antagonist co-activation in older adults is consistent with studies of muscles around both the trunk (Asaka & Wang, 2008; de Freitas et al., 2010; Kuo et al.,

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2011; McGill et al., 1999), and other joints (Hoffren, Ishikawa, & Komi, 2007; Hortobagyi & DeVita, 2000; Hortobgyi, Finch, Solnik, Rider, & DeVita, 2011). In part higher antagonist activation could be explained by lower abdominal strength of older compared to younger adults (Hasue et al., 1980; Kubo, 1994; Sinaki et al., 2001) but could also reflect the need for increased active spinal stiffness as shown in younger adults (Arjmand et al., 2008a; Brown & Potvin, 2005; Granata & Marras, 2000; Vera-Garcia, Brown, Gray, & McGill, 2006). Computer optimization models suggest that neural drive to the spine is partially explained by maintaining stiffness requirement (Brown & Potvin, 2005; Rashedi et al., 2010). Hence, reduced neutral zone passive stiffness (Sengupta & Fan, 2014) associated with disc degeneration (Siemionow, An, Masuda, Andersson, & Cs Szabo, 2011) in older adults could require increased active stiffness beyond that used in younger participants, as shown around the knee and ankle (Hoffren et al., 2007; Hortobagyi & DeVita, 2000).

Differences in PC1 scores between sides are indicative of an asymmetric neural drive shown for specific back and abdominal muscles in younger and older adults, particularly in maximum reach. For older adults the asymmetry for the abdominal sites with increasing task intensity was not confined to one direction as higher left versus right neural drive was found for the IO and EO2 muscle sites whereas the LRA and EO1 sites had higher right versus left site activity. Only IO had higher left versus right activity in younger adults. For the back muscles the asymmetry with maximum reach was consistent with higher right versus left activity for all muscle sites although only four were significantly higher. This could be explained as a compensation for cross sectional area differences between muscle pairs as cross sectional area difference between sides of erector spinae muscles have been reported in approximately 50% of a healthy adult population (35–69 years old) (Fortin, Yuan, & Battie, 2014). Of note is that these asymmetries in particular in the abdominals were not systematic among muscle sites, so a simple structural explanation might not suffice. Future studies could establish the extent that these differences are explained by neural drive or cross sectional area, but more sophisticated biomechanical modeling is needed to determine whether these asymmetries result in relative stiffness and joint loads asymmetries (Kavcic et al., 2004; Marras, Davis, & Jorgensen, 2003; Marras, Ferguson, Q5 Burr, Davis, & Gupta, 2004).

4.3. Older adults have altered temporal activation patterns of trunk muscles

Temporal features of EMG waveforms or relative changes over the entire task were captured primarily by responses to the changing lateral flexion moment (PC2) consistent with previous work (Hubley-Kozey et al., 2012, 2013). For all but two medial (LL33 & LL52) back sites older adults had greater response to lateral flexion moments (higher absolute PC2 scores) compared to younger adults (Fig. 5d). Higher relative activity at the beginning and end of the transfer task in older adults could in part reflect lower lateral flexor strength, where increasing task intensity results in increased responses in muscles that can counterbalance a lateral flexion moment (Table 4). For the abdominals, the lower PC2 score magnitudes (closer to zero) in the left posterior external oblique muscle sites (EO3) in older adults compared to younger adults (Fig. 5c) during maximum reach suggests less responsiveness to the lateral flexion moment throughout the task. While older adults had an initial burst in LEO3 activity in response to lift off (high right lateral flexion moment) for maximum reach (Fig. 2g), there was no gradual decrease in activity as the lateral moment decreased during LHT (i.e. high left lateral flexion moment). This temporal pattern with reduced differential in activity between RHT and LHT indicates more sustained activation for older adults in the posterior external oblique sites rather than modulating activation to the lateral flexion moment as shown by younger adults. Given the contribution of the external oblique fibers to produce lateral flexion moments (Dumas et al., 1991), older adults would have an inefficient pattern as these sites produce an antagonistic moment during LHT.

More sustained abdominal muscle activation is consistent with changes seen for older adults performing a leg loading exercise (Hubley-Kozey et al., 2009) as well as individuals recovered from a low back injury performing the same lifting task (Hubley-Kozey et al., 2013). Recruitment pattern similarities between older adults and low back injured populations' could reflect a common mechanisms as proprioception deficits (Goldberg et al., 2005; Lee, Cholewicki, Reeves, Zazulak, & Mysliwiec, 2010) and delayed onsets of trunk muscles to unanticipated perturbations (Allman & Rice, 2002; de Freitas et al., 2010; Hodges, 2001; Hwang et al., 2008; Silfies, Mehta, Smith, & Karduna, 2009) have been reported compared to healthy young populations. To compensate for these changes, low back pain populations utilize more continuous activation of agonist, and antagonist muscles (D'hooge et al., 2013; Hubley-Kozey et al., 2013) a pattern that can increase active spinal stiffness (Stokes, Gardner-Morse, Henry, & Badger, 2000; Vera-Garcia et al., 2006). Increased active stiffness could also compensate for reduced passive spinal stiffness from increased joint laxity in the neutral zone (Gallagher et al., 2007) associated with age and injury related joint space narrowing (De Schepper et al., 2010; Hangai et al., 2008; Hicks, Morone, & Weiner, 2009).

The implication of the combined effect of continuous muscle activation, and increased agonist and antagonist activation is increased spinal stability (resistance to motion) (Brown, Vera-Garcia, & McGill, 2006; Stokes et al., 2000), but at a potential cost of greater cumulative loading (Granata & Marras, 2000; Vera-Garcia et al., 2006) leading to a risk of disc degeneration (Wang, Jiang, & Dai, 2007), and increased risk of trunk muscle fatigue (Yassierli, Nussbaum, Iridiastadi, & Wojcik, 2007). Both increased joint loading and muscle fatigue are risk factors for low back injuries (Davidson, Madigan, Southward, & Nussbaum, 2011; Davidson et al., 2009; Norman et al., 1998). However, to determine whether age-related changes in neuromuscular activation patterns alter spinal loading or spinal stiffness requires detailed three-dimensional modeling of the spine, as age-related changes result in a non-uniform decline in strength (Hasue et al., 1980; Kubo, 1994; Sinaki et al., 2001), cross sectional area (Anderson, D'Agostino, Bruno, Manoharan, & Bouxsein, 2012; Hicks et al., 2005a; Ikezoe, Mori, Nakamura, & Ichihashi, 2012; Ota, Ikezoe, Kaneoka, & Ichihashi, 2012) and muscle quality (Anderson et al., 2012; D'Antona et al., 2003; Hicks et al., 2005b) in different abdominal and back extensor muscle fibers.

4.4. Older adults have altered trunk muscle synergies

An unexpected finding was the change in synergies among the oblique abdominal muscle sites. In younger adults ipsilateral anterior oblique fibers (EO1) shared a temporal synergy with the horizontal fibers of the IO whereas the ipsilateral lateral (EO2) and EO3 fibers shared a synergy in response to lateral flexion (Fig. 6a) as previously reported (Hubley-Kozey et al., 2012). In contrast, older adults EO1 fibers shared a temporal synergy with the posterior more vertically oriented EO3 fibers and there was no temporal synergy between ipsilateral EO2 and EO3 fibers (Fig. 6b, Table 3). This temporal EO1/IO synergy in younger adults is consistent with a rotational moment balance during the first 10% of the task when REO1 should produce a left axial rotation moment, stabilizing the right rotation produced by the left lateral (LEO2) and posterior fibers (LEO3) of the external oblique (Arjmand et al., 2008b; Dumas et al., 1991). In the older adults, lower initial EO2 activity relative to final activity (high PC2 scores) (Fig. 5c) would produce less right axial rotation during RHT, subsequently requiring a lower corrective moment produced by REO1 fibers. Older adults had slightly more trunk axial rotation (Table 2) which in part agrees with studies of unconstrained trunk motion, where older adults produced trunk movement in undesired planes, particularly axial rotation (McGill et al., 1999; Van Emmerik et al., 2005). The greatest difference between groups was during task initiation (approximately 2°) but the total motion of 3.2° also had a large variability indicating a greater range in axial motion among older adults. Hence, changes in oblique muscle fiber synergies could contribute to inappropriate control of rotational moments in older adults, and interestingly decreased control of upper trunk axial rotation acceleration during gait is a predictor of fall risk in older adults (Doi et al., 2013). However, further study is needed to determine whether there is a link between undesired axial rotation and an inability to fine tune specific temporal synergies of muscle fibers in older adults by investigating uncontrolled tasks such as walking.

Older adults had similar shaped responses to the lateral flexion moment (PC2 scores) for superficial fibers of the posterior quadratus lumborum (L48) muscle and the inferior iliocostalis sites (L36) indicative of a temporal synergy (Fig. 6c) whereas younger adults had less responsive in L48 to the lateral moment (lower PC2 score) compared to the inferior iliocostalis (L36) (Table 4). Increased quadratus lumborum activity was previously reported in response to frontal/lateral loading, and was explained as an attempt to distribute lateral flexor moment across agonist sites for a low back pain population (Park, Tsao, Cresswell, & Hodges, 2013) which in part explain the older adult findings. The muscle by reach interaction showed that increased task intensity reduced the synergy between LL48 and LL36,

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thus the older adult synergy is likely not explained by muscle strength and task intensity only (Table 4).

Since trunk muscles exhibit directionally specific reflexive activity to restore balance (Masani et al., 2009), the inability to fine-tune the EO and lateral back extensors might reflect diminished reflexive activation reported at other joints in older adults (Granacher, Gollhofer, & Strass, 2006; Kido, Tanaka, & Stein, 2004; Obata, Kawashima, Akai, Nakazawa, & Ohtsuki, 2010). Other explanations for altered recruitment in EO and L48 sites in older adults could be explored such as less focal recruitment of the motor cortex, (Van Impe et al., 2011) resulting in activation of motor units in neighboring fibers. These explanations are purely speculative but measuring reflex responses and mapping cortical activity during a controlled task might help differentiate the source of the alteration in trunk activation patterns. In general this overall lack of differential recruitment could be problematic in instances where specific muscle responses to perturbations are required to produce a corrective moment such as in a backward fall which would require selective recruitment of the abdominal musculature for example.

4.5. Limitations

Potential limitations in interpreting surface EMG findings exist. First, is whether older adults can produce maximal effort contraction for EMG normalization compared to a younger population (McGill et al., 1999), but older adults showed the same ability to maximally activate their muscles as younger adults at other joints (Klass, Baudry, & Duchateau, 2005). In addition, older adults did not report discomfort while performing trunk maximum voluntary contractions (Hanada et al., 2008), nor did they in this study. If this bias existed it would only affect PC1 scores and differences were not systematic among all muscle sites between groups nor were the differences uniform throughout the task for all muscle sites (Figs. 2 and 3). Second is the potential for cross talk and precautions were taken to minimize cross talk through maximizing electrode placement between adjacent muscles (Fuglevand, Winter, Patla, & Stashuk, 1992) and by performing validation exercises (Winter, Fuglevand, & Archer, 1994). Sites such as the quadradus lumborum and multifidus pose the greatest concern but this paper and others (Ceccato, de-Seze, Azevedo, & Cazalets, 2009; Hubley-Kozey et al., 2012, 2013) identify that both multifidus and quadratus lumborum sites do have unique muscle activation patterns relative to their nearby erector spinea fibers longissimus and iliocostalis. While there is the potential for cross talk, the subtle differences in responses support that the predominant motor unit activity picked up by the electrode are from the underlying muscles consistent with the electrophysiology and volume properties of the tissues involved. Finally significant differences for the trunk motion were found between groups and for trunk flexion with increased reach distance for both groups. However, differences less than 1° would have minimal effect on the external flexion and lateral flexion external moments based on standard calculations using estimates of trunk mass as previously reported (approximately 0.3 Nm or a 1% increase for the maximum reach task) (Hubley-Kozey et al., 2012). The significant difference more likely reflect the very small variability due to the task constraints having minimal effect on external moments or EMG–force relationship differences (Brown & McGill, 2008) and hence minimal contribution to the interpretation of the EMG differences between groups or reach.

4.6. Summary of electromyographic findings

In summary the results of this study support overall higher activity as a percentage of maximum for the older adults which has implications for increased risk of fatigue, but this cannot, without additional modeling be related directly to increased muscle force, limiting conclusions around higher active stiffness and joint loading. However, what the findings do show is that the pattern of loading throughout the task is different based on the temporal pattern alterations and differences in synergies between the two groups. Together these could change the dynamic loading pattern of an older adult spine and the time varying pattern of spinal stiffness.

5. Conclusion

In conclusion, healthy older adults performed a controlled lift and replace task with similar time to complete task and only small differences in trunk motion; hence they produced similar external dynamic moments of force that their trunk musculature had to counterbalance as a young group. Consistent with our hypotheses, older adults recruited higher agonist and antagonistic activation, demonstrated sustained activation levels despite changing flexion and lateral flexion moments throughout the task in specific muscle sites and had differences in the temporal response of specific muscle sites indicative that healthy aging alters trunk muscle synergies. Examining synergies including temporal synergies among trunk muscle sites has added to our knowledge of age related changes in trunk muscle function having implications for understanding trunk control and spine stability in the aging population.

6. Uncited references

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