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Full Length Article

Arm position influences the activation patterns of trunk muscles during trunk range-of-motion movements

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ABSTRACT

To understand the activation patterns of the trunk musculature, it is also important to consider the implications of adjacent structures such as the upper limbs, and the muscles that act to move the arms. This study investigated the effects of arm positions on the activation patterns and co-activation of the trunk musculature and muscles that move the arm during trunk range-of-motion movements (maximum trunk axial twist, flexion, and lateral bend). Fifteen males and fifteen females, asymptomatic for low back pain, performed maximum trunk range-of-motion movements, with three arm positions for axial twist (loose, crossed, abducted) and two positions for flexion and lateral bend (loose, crossed). Electromyographical data were collected for eight muscles bilaterally, and activation signals were cross-correlated between trunk muscles and the muscles that move the arms (upper trapezius, latissimus dorsi). Results revealed consistently greater muscle co-activation (higher cross-correlation coefficients) between the trunk muscles and upper trapezius for the abducted arm position during maximum trunk axial twist, while results for the latissimus dorsi-trunk pairings were more dependent on the specific trunk muscles (either abdominal or back) and latissimus dorsi muscle (either right or left side), as well as the range-of-motion movement. The findings of this study contribute to the understanding of interactions between the upper limbs and trunk, and highlight the influence of arm positions on the trunk musculature. In addition, the comparison of the present results to those of individuals with back or shoulder conditions may ultimately aid in elucidating underlying mechanisms or contributing factors to those conditions.

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1. Introduction

There is an extensive body of literature regarding spine mechanics in terms of motion characteristics and the muscle activation that produces that motion. The muscles responsible for spinal motion in each plane (flexion-extension, lateral bend, and axial twist) have been identified, based upon physiological cross-sectional area and lines of action of each muscle (McGill, Santaguida, & Stevens, 1993). For example, flexion and extension movements occur through activation of the abdominal and erector spinae muscle groups (Floyd & Silver, 1955), respectively. Lateral bending is primarily accomplished by the intertransversarii and oblique muscles (Lavender, Chen, Trafimow, & Andersson, 1995) while axial twisting is

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accomplished by the rotatores and oblique muscles (Pope, Andersson, Broman, Svensson, & Zetterberg, 1986). McGill (1991) also identified the latissimus dorsi and erector spinae as contributing to trunk axial twist. However, the muscle activation characteristics of the trunk, and interactions between trunk muscles to produce motion, are not as clearly understood as trunk motion patterns.

Muscle activation plays an important role in regulating spinal stiffness, and consequently spinal stability. The stiffness of the spine represents the amount of translational or rotational deformation a spinal segment may undergo when exposed to an applied force (White & Panjabi, 1978). Activation of the musculature acts to increase the stiffness of the spine (Brown & McGill, 2005, 2008; Lee, Rogers, & Granata, 2006), thereby contributing to stability and preventing buckling of the spine during loading, static postures, and motion (McGill, Grenier, Kavcic, & Cholewicki, 2003). Activation that is either insufficient or excessive to maintain stability may result in spinal buckling or increased compression forces, respectively, increasing the risk of injury in both scenarios (Cholewicki & McGill, 1996). The coordinated activation of the collective trunk musculature is necessary to maintain sufficient spinal stiffness and stability, as the inappropriate activation of a single muscle may facilitate spinal instability (McGill et al., 2003). Therefore, an understanding of activation patterns within the trunk is essential to better understand injury risk in the spine.

There is also clinical relevance for muscle activation characteristics. Cross-correlation has been used previously to quantify patterns of activation between two muscles (Nelson-Wong, Alex, Csepe, Lancaster, & Callaghan, 2012; Nelson-Wong & Callaghan, 2010; Nelson-Wong, Gregory, Winter, & Callaghan, 2008; Nelson-Wong et al., 2013; Schinkel-Ivy & Drake, 2015a), with altered activation patterns identified in individuals with transient or chronic LBP relative to healthy individuals (Nelson-Wong & Callaghan, 2010; Nelson-Wong et al., 2008, 2012, 2013). To further emphasize the potential of evaluating activation patterns as a diagnostic tool for LBP, differences in low back activation patterns during trunk flexion have been documented based on LBP status (Colloca & Hinrichs, 2005; Floyd & Silver, 1955; Watson, Booker, Main, & Chen, 1997). These findings underscore the importance of trunk muscle activation patterns in determining the mechanisms and effects of LBP.

The majority of studies regarding activation patterns focus exclusively on the trunk musculature (Shan et al., 2014) or relationships within the lumbopelvic musculature (Nelson-Wong et al., 2013) and between the lumbopelvic and thigh musculature (Nelson-Wong et al., 2012). However, it is important to consider more superior components of the musculoskeletal system such as the arms because they may also influence the activation patterns of the trunk musculature. Past work has investigated and highlighted the possible implications of arm movement on the trunk. For example, in walking with and without arm swing movements, increased activation of the trunk musculature was reported with restricted arm swing (Callaghan, Patla, & McGill, 1999). With arm movements at varying speeds, Hodges and Richardson (1999) showed differences in trunk musculature recruitment in individuals with LBP. In functional tasks such as lifting, Crosbie, Kilbreath, and Dylke (2010) reported coordinated kinematic movement patterns between the scapulae and spine. Additionally, Schinkel-Ivy, Pardisnia, and Drake (2014) identified differences in trunk range of motion during maximum trunk flexion, lateral bend, and axial twist with different arm positions. However, work addressing the effects of arm position and trunk movement on muscle activation patterns, and relationships in activation patterns of the muscles that move the trunk and arms, is currently limited. Providing a more in-depth understanding of the relationships between the trunk and arm musculature will contribute to the study of LBP, as activation characteristics of the trunk have been related to both pain (Nelson-Wong, Howarth, & Callaghan, 2010; Nelson-Wong et al., 2012, 2013) and injury (Cholewicki & McGill, 1996; McGill, 1992; McGill et al., 2003) development. This study aimed to investigate the effects of arm position on the activation patterns (specifically co-activation) of the trunk musculature and muscles that move the arm during trunk range-of-motion movements (maximum trunk axial twist, flexion, and lateral bend).

2. Methods

2.1. Participants

Thirty right-handed individuals, 15 males (mean (SD) age, 25.0 (3.8) y; height, 1.80 (0.05) m; weight, 79.64 (8.75) kg) and 15 females (mean (SD) age, 22.8 (2.7) y; height, 1.66 (0.05) m; weight, 59.12 (6.38) kg), participated in this study. All participants were asymptomatic for back pain, defined as not having sought treatment or missed any days of school or work due to back pain for 12 months. This study was approved by York University's Office of Research Ethics, and written informed consent was obtained prior to collection.

2.2. Instrumentation

Electromyography (EMG) data were collected, differentially amplified (frequency response 10–1000 Hz, common mode rejection 115 dB at 60 Hz, input impedance 10 GΩ; AMT-8, Bortec, Calgary, Canada), and sampled at 2400 Hz (Vicon MX, Vicon Systems Ltd., Oxford, UK). Sixteen pairs of disposable Ag/Ag-Cl electrodes (Ambu® Blue Sensor N, Ambu A/S, Denmark) were applied over eight muscles bilaterally (Schinkel-Ivy & Drake, 2015a): external oblique (EO), 15 cm lateral to the umbilicus at a 45° angle (McGill, 1991; Mirka & Marras, 1993); internal oblique (IO), superior to the inguinal ligament below the external oblique electrodes (McGill, 1991); rectus abdominis (RA), 2 cm superior to the umbilicus and 3 cm lateral to the midline (Mirka & Marras, 1993); lumbar erector spinae (lumbar ES), 4 cm from the midline or over the largest muscle mass at the level of L_3 (Mirka & Marras, 1993; Zipp, 1982); lower-thoracic erector spinae (lower-thoracic ES), 5 cm lateral from the midline or over the largest muscle mass at the level of T_9 (McGill, 1991; Zipp, 1982); upper-thoracic erector spinae (upper-thoracic ES), 5 cm lateral from the spinous process or over the largest muscle mass at T_4 (Burnett et al., 2009; Zipp, 1982); latissimus dorsi (LAT), the most lateral portion of the muscle at the level of T_9 (McGill, 1991); and upper trapezius (TRAP), 2 cm lateral to the midpoint of a line drawn between the spinous process of C_7 and posterolateral acromion (Jensen, Vasseljen, & Westgaard, 1993).

2.3. Procedures

Prior to electrode application, the electrode sites were shaved and swabbed with rubbing alcohol to promote electrode adherence and minimize skin impedance. Following electrode placement, maximum voluntary contractions (MVC) were obtained for the trunk, LAT, and TRAP muscles. For the trunk flexors, a protocol was adapted from McGill (1992) in which the trunk was isometrically flexed, bent, and twisted against manual resistance. For the trunk extensors, the trunk was cantilevered at the hip over the edge of a therapy table and participants performed an isometric back extension against manual resistance (McGill, 1992). For MVC of the LAT muscles, the shoulder was abducted to 90°, with the arm externally rotated and the elbow flexed to 90°. In this position, participants pulled their elbow in a downwards direction against manual resistance (Arlotta, LoVasco, & McLean, 2011). For MVC of the TRAP muscles, the arm was abducted and held at a 90° position, and participants abducted their arm in an upwards direction against manual resistance (McLean, 2005). Three trials lasting 3–5 s each were performed for each muscle grouping, with the trials separated by 3 min of rest to minimize the onset of fatigue. The maximum EMG value for each muscle obtained during the three trials was designated as the MVC.

Following marker application, a kinematic calibration trial was performed with the participant maintaining a quiet standing position with the arms abducted to 90° ('T-pose'). A total of 70 experimental trials were then presented in a random order. Experimental trials consisted of standing maximum trunk ROM tasks in each plane of movement (axial twist, flexion, and lateral bend), with three arm position conditions for maximum axial twist (arms crossed over the chest (crossed), arms abducted to 90° (abducted), or arms hanging down to the sides (loose)), and two arm position conditions for maximum flexion and maximum lateral bend (crossed; arm(s) hanging down to the floor (loose)) (Fig. 1). While participants maintained these arm positions throughout the trials, they were allowed to choose their most comfortable/natural position (for example, within the crossed arm position, participants chose which arm was crossed on top). This approach was selected to facilitate participants achieving their maximum range of motion.

All bending and twisting trials were performed to the right side. Participants were given full instructions for each task prior to the protocol as well as time to practice. Between trials, prompts were given to participants to relay the task required for the next trial. Participants were instructed to initiate movement by leading with the head in the plane of motion, followed by subsequent trunk movement in the same direction in a continuous and controlled manner until full trunk ROM was reached. At full trunk ROM, participants held the position for 3 s and then returned to upright standing. All trials lasted approximately 10 s.

2.4. Data processing

Raw EMG data were processed using Visual3D v.4 (C-Motion, Inc., Germantown, USA). Heart rate contamination in the raw data was reduced using a dual-pass, 4th order, Butterworth filter, with a cutoff frequency of 30 Hz (Drake & Callaghan, 2006). Data were then full-wave rectified and low-pass filtered with a 4th order, Butterworth filter with a cutoff frequency of 2.5 Hz (Brereton & McGill, 1998; Van Dieen & Kingma, 2005). The MVC for each muscle was used for normalization of the EMG signals from the experimental trials, such that EMG data were expressed as a percentage relative to each individual's maximum activation levels (%MVC). Maximum activation levels from each experimental trial were obtained and

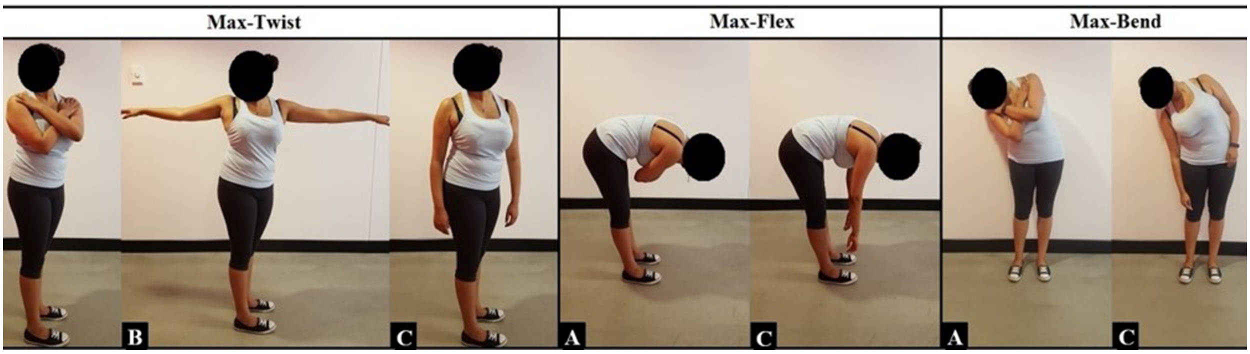

Fig. 1. Arm positions tested for each movement. A: crossed arm position (max-twist, max-flex, and max-bend); B: abducted arm position (max-twist only); C: loose arm position (max-twist, max-flex, and max-bend).

Table 1
Mean (SD) activation levels (%MVC) for each muscle during each movement. L/R: left/right; **TRAP: upper trapezius**; *LAT: latissimus dorsi*; EO: external oblique; IO: internal oblique; RA: rectus abdominis; LES: lumbar erector spinae; LTES: lower-thoracic erector spinae; UTES: upper-thoracic erector spinae.

	Max-twist			Max-flex		Max-bend	
	Crossed	Abducted	Loose	Crossed	Loose	Crossed	Loose
LTRAP	14.0 (10.2)	24.8 (12.2)	6.3 (4.8)	12.5 (8.4)	6.8 (4.8)	14.0 (8.4)	5.5 (4.6)
RTRAP	14.3 (8.1)	24.5 (13.9)	4.6 (2.8)	10.3 (4.5)	6.7 (3.6)	15.9 (10.3)	7.4 (5.3)
LLAT	9.6 (4.3)	7.7 (3.2)	5.2 (2.9)	9.9 (6.2)	8.2 (4.2)	10.8 (5.0)	10.3 (7.8)
RLAT	14.6 (8.3)	13.4 (9.9)	16.6 (11.5)	10.2 (5.2)	9.4 (4.0)	7.3 (3.9)	5.1 (2.0)
LEO	34.2 (17.0)	31.1 (17.0)	29.7 (16.4)	15.2 (9.1)	14.5 (8.9)	43.1 (22.4)	42.1 (19.9)
REO	40.1 (22.3)	40.5 (22.5)	35.3 (20.5)	11.5 (5.3)	12.0 (5.4)	17.3 (11.5)	14.4 (7.5)
LIO	17.5 (12.4)	16.7 (11.5)	15.8 (10.4)	16.9 (9.2)	15.8 (9.6)	28.7 (21.6)	25.0 (17.9)
RIO	29.5 (21.2)	31.5 (25.4)	28.5 (20.9)	14.3 (9.5)	13.9 (9.4)	13.5 (8.5)	12.0 (7.1)
LRA	9.6 (7.6)	10.1 (6.5)	9.6 (6.4)	17.3 (14.5)	15.9 (13.0)	13.2 (10.9)	15.0 (13.8)
RRA	10.8 (7.5)	12.9 (8.5)	10.9 (7.6)	15.6 (14.4)	13.0 (8.2)	9.8 (7.5)	9.8 (6.4)
LLES	14.3 (8.9)	9.3 (7.8)	8.8 (7.2)	40.0 (14.6)	35.8 (12.4)	20.7 (9.7)	12.7 (6.2)
RLES	12.8 (5.9)	13.9 (7.2)	11.9 (6.1)	37.8 (15.7)	34.3 (13.7)	9.0 (4.0)	6.5 (3.9)
LLTES	7.6 (3.4)	7.5 (3.5)	4.7 (2.3)	18.2 (7.2)	16.0 (7.0)	12.6 (5.5)	6.0 (2.9)
RLTES	32.8 (18.3)	24.7 (17.2)	20.1 (15.4)	17.5 (8.8)	16.3 (9.1)	9.0 (5.1)	6.8 (3.5)
LUTES	5.7 (2.2)	20.4 (9.0)	5.0 (2.0)	8.3 (3.9)	8.8 (4.4)	10.2 (5.8)	6.1 (3.2)
RUTES	29.6 (14.5)	55.5 (17.3)	26.7 (16.2)	9.1 (3.9)	9.6 (4.3)	6.8 (2.5)	6.6 (2.3)

Table 2
All bilateral pairings between the upper trapezius and trunk muscles, and latissimus dorsi and trunk muscles. L/R: left/right; TRAP: upper trapezius; *LAT: latissimus dorsi*; EO: external oblique; IO: internal oblique; RA: rectus abdominis; LES: lumbar erector spinae; LTES: lower-thoracic erector spinae; UTES: upper-thoracic erector spinae.

LTRAP–Trunk Pairings	**RTRAP**–Trunk Pairings	*LLAT*–Trunk Pairings	*RLAT*–Trunk Pairings
LTRAP-LEO	**RTRAP**-LEO	*LLAT*-LEO	*RLAT*-LEO
LTRAP-REO	**RTRAP**-REO	*LLAT*-REO	*RLAT*-REO
LTRAP-LIO	**RTRAP**-LIO	*LLAT*-LIO	*RLAT*-LIO
LTRAP-RIO	**RTRAP**-RIO	*LLAT*-RIO	*RLAT*-RIO
LTRAP-LRA	**RTRAP**-LRA	*LLAT*-LRA	*RLAT*-LRA
LTRAP-RRA	**RTRAP**-RRA	*LLAT*-RRA	*RLAT*-RRA
LTRAP-LLES	**RTRAP**-LLES	*LLAT*-LLES	*RLAT*-LLES
LTRAP-RLES	**RTRAP**-RLES	*LLAT*-RLES	*RLAT*-RLES
LTRAP-LLTES	**RTRAP**-LLTES	*LLAT*-LLTES	*RLAT*-LLTES
LTRAP-RLTES	**RTRAP**-RLTES	*LLAT*-RLTES	*RLAT*-RLTES
LTRAP-LUTES	**RTRAP**-LUTES	*LLAT*-LUTES	*RLAT*-LUTES
LTRAP-RUTES	**RTRAP**-RUTES	*LLAT*-RUTES	*RLAT*-RUTES

averaged across the 10 trials of each condition, then across participants; these values are provided in Table 1 to contextualize the movements involved in the study. EMG data were then downsampled from 2400 Hz to 50 Hz as a data reduction measure (Nelson-Wong & Callaghan, 2010).

Cross-correlation was used to quantify the spatial and temporal similarities between activation patterns of specific pairings of muscles (Nelson-Wong, Howarth, Winter, & Callaghan, 2009). Briefly, cross-correlation describes the linear relationship between each sample of two input signals with no time lag or a specified time lag (Nelson-Wong et al., 2009). The linear relationship at each sample is equally weighted across the time series to determine the cross-correlation coefficient (Nelson-Wong et al., 2009). Calculated coefficients vary between −1.0 and +1.0, with negative and positive values indicating that two signals change in opposite or the same directions relative to each other, respectively (Nelson-Wong et al., 2009). For each trial, cross-correlation time series were calculated between each of the trunk muscles (left and right EO, IO, RA, lumbar ES, lower-thoracic ES, and upper-thoracic ES) relative to the left and right LAT, and to the left and right TRAP (48 pairings in total; Table 2), using Matlab v.R2012a (The MathWorks, Inc., Natick, USA). The cross-correlation coefficients at a time lag of zero (R_{xy}) were then extracted for each trial (Johnson, Cacciatore, Hamill, & Van Emmerik, 2010; Schinkel-Ivy & Drake, 2015b), indicating the strength of the relationships between the activation patterns of the specified pairing of muscles over the activation time series (Lee & Wong, 2002; Shum, Crosbie, & Lee, 2005, 2007; Wong & Lee, 2004); that is, the extent to which the changes in the two signals were similar. The mean cross-correlation coefficient for each condition was then determined for each participant.

2.5. Data analysis

Two-factor mixed ANOVAs were conducted to compare cross-correlation coefficients for each pairing between the arm conditions for each movement task. The between-group factor was sex, while the repeated measure was arm condition (max-twist: 3 levels; max-flex, max-bend: 2 levels). Data were collapsed across sex where there were no significant effects of that factor. Pairwise comparisons with a Bonferroni correction were used for post hoc testing where applicable, and alpha was set to 0.05. Cross-correlation coefficients of ±0.00–0.19, 0.20–0.39, 0.40-0.59, 0.60-0.79 and 0.80-1.00 were considered very weak, weak, moderate, strong, and very strong, respectively (Swinscow, 1997).

3. Results

Significant main effects of arm position or interactions between arm position and sex were observed for the majority of TRAP-trunk pairings during max-twist (Table 3). Generally, significant post hoc comparisons indicated that the greatest cross-correlation coefficients were produced in the abducted arm position (weak and moderate magnitudes). For max-flex and max-bend movements, few differences in TRAP-trunk coefficients were observed between arm positions, with very weak or weak magnitudes. Overall, the greatest coefficients were observed when the arms were abducted in max-twist, with no clear trends for max-flex or max-bend.

Across all three movements, there was a significant main effect of arm position on cross-correlation coefficients for the majority of LAT-back pairings (upper-thoracic ES, lower-thoracic ES, lumbar ES) (Table 4). Generally, the loose arm position yielded greater cross-correlation coefficients in most muscle pairings; the exception was LLAT-back muscle pairings for max-twist, in which the greatest coefficients were identified for either the loose or crossed position. Cross correlation coefficients between the LAT and back muscles in max-twist, max-flex, and max-bend tended to be of a moderate or strong, weak or moderate, and very weak to strong magnitude, respectively. These findings suggested differential effects of arm position for LAT-back pairings depending on the movement, with the loose arm position generally facilitating the greatest coefficients.

For LAT-abdominal (EO, IO, RA) pairings, the significant main effect of arm position or interactions between arm position and sex on cross-correlation coefficients varied across the three movements (Table 5). For the LLAT-abdominal pairings during max-twist, the crossed arm position generally yielded greater cross-correlation coefficients than the abducted or

Table 3
Mean (SD) cross-correlation coefficients of TRAP-trunk pairings for the three arm positions for max-twist. Separate means for males and females are specified for pairings with a significant interaction with sex and arm position. L/R: left/right; TRAP: upper trapezius; EO: external oblique; IO: internal oblique; RA: rectus abdominis; LES: lumbar erector spinae; LTES: lower-thoracic erector spinae; UTES: upper-thoracic erector spinae; M/F: male/female.

Pairing	Sex	Arm position		
		Crossed	Abducted	Loose
LTRAP-LEO	M	−0.112 (0.406) [1]	0.383 (0.272) [2]	0.010 (0.301)
	F	0.001 (0.309) [1]	0.224 (0.280) [2]	−0.080 (0.294)
LTRAP-REO	M	−0.098 (0.352) [1]	0.320 (0.222) [2]	−0.007 (0.297)
	F	0.076 (0.332) [1]	0.276 (0.314) [2]	−0.057 (0.320)
LTRAP-LIO	M	−0.120 (0.330) [1]	0.140 (0.330)	0.000 (0.204)
	F	0.006 (0.196)	−0.023 (0.260)	−0.090 (0.204)
LTRAP-RIO	M	−0.085 (0.357) [1]	0.342 (0.220) [2]	−0.012 (0.292)
	F	0.055 (0.311)	0.234 (0.287) [2]	−0.085 (0.284)
LTRAP-LRA	–	−0.032 (0.314) [1]	0.168 (0.252) [2]	−0.033 (0.224)
LTRAP-RRA	M	−0.094 (0.310) [1]	0.248 (0.227) [2]	0.024 (0.224)
	F	0.052 (0.330)	0.179 (0.294) [2]	−0.045 (0.255)
LTRAP-LLES	–	0.005 (0.293)	0.148 (0.239) [2]	−0.035 (0.223)
LTRAP-RLES	M	−0.068 (0.267) [1]	0.321 (0.240) [2]	−0.014 (0.280)
	F	0.097 (0.283) [2]	0.245 (0.296) [2]	−0.087 (0.284)
LTRAP-LLTES	–	0.062 (0.202)	0.090 (0.269)	−0.020 (0.242)
LTRAP-RLTES	M	−0.130 (0.371) [1]	0.344 (0.250) [2]	−0.013 (0.324)
	F	0.060 (0.307) [1]	0.253 (0.291) [2]	−0.092 (0.336)
LTRAP-LUTES	–	0.007 (0.278) [1]	0.188 (0.313)	0.026 (0.280)
LTRAP-RUTES	–	−0.036 (0.367) [1]	0.348 (0.291) [2]	−0.038 (0.317)
RTRAP-LEO	–	0.150 (0.386) [1]	0.441 (0.271) [2]	0.078 (0.388)
RTRAP-REO	–	0.183 (0.358) [1]	0.451 (0.237) [2]	0.136 (0.358)
RTRAP-LIO	–	−0.023 (0.266)	0.151 (0.364)	0.026 (0.291)
RTRAP-RIO	–	0.159 (0.345) [1]	0.416 (0.229) [2]	0.119 (0.337)
RTRAP-LRA	–	0.112 (0.312)	0.302 (0.285) [2]	0.051 (0.317)
RTRAP-RRA	–	0.142 (0.304) [1]	0.363 (0.229) [2]	0.086 (0.330)
RTRAP-LLES	–	0.141 (0.306)	0.285 (0.282) [2]	0.068 (0.269)
RTRAP-RLES	–	0.159 (0.306) [1]	0.479 (0.251) [2]	0.109 (0.344)
RTRAP-LLTES	–	0.025 (0.204)	−0.026 (0.269)	0.097 (0.256)
RTRAP-RLTES	–	0.153 (0.381) [1]	0.457 (0.259) [2]	0.070 (0.394)
RTRAP-LUTES	–	0.116 (0.274) [1]	−0.161 (0.315) [2]	0.100 (0.329)
RTRAP-RUTES	–	0.137 (0.390) [1]	0.551 (0.265) [2]	0.070 (0.410)

[1] Significant difference from abducted arm position for that pairing ($p < 0.05$).
[2] Significant difference from loose arm position for that pairing ($p < 0.05$).

Table 4
Mean (SD) cross-correlation coefficients of LAT-back for all movement tasks. Separate means for males and females are specified for pairings with a significant interaction with sex and arm position. L/R: left/right; *LAT: latissimus dorsi*; LES: lumbar erector spinae; LTES: lower-thoracic erector spinae; UTES: upper-thoracic erector spinae; M/F: male/female.

Pairing	Sex	Max-twist			Sex	Max-flex		Sex	Max-bend	
		Crossed	Abducted	Loose		Crossed	Loose		Crossed	Loose
LLAT-LLES	–	0.514 (0.217)[1,2]	0.381 (0.244)	0.429 (0.180)	–	0.224 (0.283)[1]	0.397 (0.250)	–	0.516 (0.217)[1]	0.354 (0.261)
LLAT-RLES	–	0.544 (0.207)	0.555 (0.182)	0.530 (0.175)	–	0.209 (0.297)[1]	0.378 (0.252)	–	−0.086 (0.268)[1]	0.153 (0.220)
LLAT-LLTES	–	0.061 (0.397)[2]	0.168 (0.297)[2]	0.556 (0.180)	–	0.278 (0.304)	0.371 (0.235)	–	0.338 (0.216)	0.421 (0.254)
LLAT-RLTES	–	0.663 (0.136)	0.570 (0.180)	0.580 (0.171)	–	0.253 (0.337)	0.374 (0.237)	M	−0.209 (0.209)[1]	0.273 (0.255)
								F	−0.010 (0.371)[1]	0.184 (0.283)
LLAT-LUTES	–	0.356 (0.324)[1]	−0.038 (0.272)[2]	0.469 (0.246)	–	0.293 (0.276)	0.278 (0.190)	M	0.184 (0.233)[1]	0.394 (0.271)
								F	0.472 (0.166)	0.368 (0.182)
LLAT-RUTES	–	0.665 (0.126)[2]	0.598 (0.179)	0.546 (0.192)	–	0.200 (0.280)	0.268 (0.229)	–	0.065 (0.273)[1]	0.212 (0.215)
RLAT-LLES	–	0.429 (0.296)[2]	0.440 (0.267)[2]	0.511 (0.248)	–	0.237 (0.251)[1]	0.443 (0.255)	–	−0.007 (0.178)	0.027 (0.180)
RLAT-RLES	–	0.674 (0.196)	0.744 (0.137)	0.750 (0.134)	–	0.231 (0.266)[1]	0.441 (0.252)	–	0.191 (0.283)[1]	0.385 (0.246)
RLAT-LLTES	–	0.062 (0.316)[2]	0.134 (0.276)[2]	0.412 (0.274)	–	0.267 (0.297)[1]	0.399 (0.242)	–	−0.005 (0.250)[1]	0.173 (0.244)
RLAT-RLTES	–	0.666 (0.236)[1,2]	0.766 (0.130)	0.803 (0.140)	–	0.307 (0.331)[1]	0.458 (0.230)	–	0.349 (0.302)[1]	0.611 (0.225)
RLAT-LUTES	–	0.359 (0.288)[1,2]	−0.030 (0.246)[2]	0.553 (0.258)	–	0.297 (0.288)	0.307 (0.205)	–	0.224 (0.258)[1]	0.366 (0.183)
RLAT-RUTES	–	0.589 (0.228)[1,2]	0.728 (0.120)	0.733 (0.175)	–	0.246 (0.266)	0.319 (0.210)	–	0.308 (0.232)	0.363 (0.167)

[1] Significant difference from abducted arm position for that pairing ($p < 0.05$).
[2] Significant difference from loose arm position for that pairing ($p < 0.05$).

Table 5
Mean (SD) cross-correlation coefficients of LAT-abdominal pairings for all movement tasks. Separate means for males and females are specified for pairings with a significant interaction with sex and arm position. L/R: left/right; *LAT: latissimus dorsi*; EO: external oblique; IO: internal oblique; RA: rectus abdominis; M/F: male/female.

Pairing	Sex	Max-twist			Sex	Max-flex		Sex	Max-bend	
		Crossed	Abducted	Loose		Crossed	Loose		Crossed	Loose
LLAT-LEO	–	0.710 (0.155)[1,2]	0.548 (0.212)	0.521 (0.234)	–	0.136 (0.233)	0.104 (0.273)	–	0.628 (0.198)[1]	0.500 (0.257)
LLAT-REO	–	0.676 (0.104)[1,2]	0.562 (0.172)	0.539 (0.177)	M	0.166 (0.160)	0.042 (0.270)	M	0.113 (0.277)	0.231 (0.309)
					F	0.116 (0.236)	0.234 (0.265)	F	0.356 (0.225)	0.274 (0.192)
LLAT-LIO	–	0.278 (0.374)	0.205 (0.337)	0.244 (0.288)	–	0.097 (0.279)	0.014 (0.292)	–	0.482 (0.217)	0.460 (0.235)
LLAT-RIO	–	0.654 (0.113)[1,2]	0.537 (0.179)	0.515 (0.169)	M	0.176 (0.213)[1]	−0.130 (0.311)	–	0.261 (0.234)	0.193 (0.293)
					F	0.182 (0.227)	0.218 (0.215)			
LLAT-LRA	–	0.635 (0.154)[1,2]	0.400 (0.289)	0.473 (0.206)	–	0.213 (0.282)	0.196 (0.265)	–	0.553 (0.135)[1]	0.427 (0.173)
LLAT-RRA	–	0.615 (0.163)[1,2]	0.446 (0.246)	0.468 (0.218)	–	0.212 (0.279)	0.222 (0.264)	–	0.399 (0.178)[1]	0.323 (0.182)
RLAT-LEO	M	0.550 (0.273)[2]	0.681 (0.149)	0.741 (0.193)	M	0.252 (0.168)[1]	0.006 (0.223)	–	0.044 (0.244)[1]	0.216 (0.230)
	F	0.565 (0.259)	0.559 (0.248)	0.568 (0.284)	F	0.011 (0.308)	0.097 (0.299)			
RLAT-REO	–	0.707 (0.188)	0.742 (0.151)	0.708 (0.145)	M	0.240 (0.190)[1]	0.009 (0.219)	–	0.156 (0.278)[1]	0.307 (0.254)
					F	0.067 (0.297)	0.202 (0.285)			
RLAT-LIO	–	0.234 (0.335)	0.230 (0.384)	0.252 (0.410)	M	0.217 (0.222)[1]	−0.106 (0.247)	–	0.098 (0.262)[1]	0.242 (0.224)
					F	−0.023 (0.354)	0.052 (0.313)			
RLAT-RIO	–	0.666 (0.198)	0.706 (0.167)	0.660 (0.172)	M	0.248 (0.235)[1]	−0.149 (0.281)	–	0.041 (0.294)	0.100 (0.283)
					F	0.122 (0.329)	0.218 (0.231)			
RLAT-LRA	–	0.535 (0.249)	0.499 (0.302)	0.500 (0.251)	–	0.204 (0.310)	0.146 (0.270)	–	0.091 (0.228)[1]	0.219 (0.178)
RLAT-RRA	–	0.629 (0.245)	0.608 (0.270)	0.574 (0.252)	–	0.200 (0.305)	0.181 (0.271)	–	0.201 (0.245)[1]	0.347 (0.165)

[1] Significant difference from abducted arm position for that pairing ($p < 0.05$).
[2] Significant difference from loose arm position for that pairing ($p < 0.05$).

loose arm positions (moderate or strong magnitude), while there were no consistent trends for the RLAT-abdominal pairings. Conversely, for max-flex, there were no consistent trends for the LLAT-abdominal pairings, while the crossed arm position elicited greater coefficients for the majority of RLAT-abdominal pairings (weak magnitude). For max-bend, the crossed and loose arm positions tended to elicit the greatest coefficients for the LLAT-abdominal (weak to strong magnitude) and RLAT-abdominal (weak magnitude) pairings, respectively. Overall, changes in cross-correlation coefficients as a result of arm position were dependent on the side of the LAT muscle (left/right), as well as the type of movement.

4. Discussion

This study provided insight into the behaviour of the trunk musculature during trunk ROM tasks, in that arm position impacted the patterns of activation between the trunk musculature and muscles that move the arm. In the TRAP-trunk pairings, the abducted arm position tended to elicit the greatest cross-correlation coefficients during max-twist, while few differences between arm positions were identified for max-flex and max-bend. For LAT-trunk pairings, the arm position producing the greatest coefficients differed based on the movement, the LAT muscle (left/right) and the antero-posterior location of the trunk muscles (abdominals/back).

The consistent trends for the abducted arm position in TRAP-trunk pairings could potentially be explained by the movement of the scapula and associated activation of the TRAP muscle, which may have changed with the arm positions adopted during max-twist movements. The TRAP muscle is involved in the control of the scapula, mainly scapular upward rotation and retraction (Faria, Teimeria-Salmela, & Gomes, 2009; Ludewig et al., 2009; Tortora, 2005). The abducted arm position involved elevation of the humerus and upward rotation of the scapula (Kibler et al., 2013; Paine & Voight, 2013), which tends to be greater during humeral elevations in the frontal plane than in the sagittal or scapular plane (Fung et al., 2001). Potentially, the greater degree of scapular movement in the abducted arm position during max-twist may have contributed to an increase in the relative contribution of the TRAP muscle, thereby resulting in consistently greater co-activation between the TRAP muscle and trunk musculature (Table 2).

While some significant differences were exhibited between arm positions for the TRAP-trunk pairings during the max-flex and max-bend movements, no consistent trends were evident with respect to the arm position eliciting the greatest cross-correlation coefficient. This may have potentially been due to limiting the max-flex and max-bend movement tasks to the crossed and loose arm positions. Many of the differences identified for max-twist were between the abducted position and the two remaining positions, with fewer differences between the crossed and loose positions. Conversely, for max-flex and max-bend, flexion at the shoulder was the primary movement for both arm positions, with less upward rotation of the scapula. Therefore, the crossed and loose arm positions may not have differed substantially enough from each other in terms of scapular rotation and associated trapezius activation to elicit differences in the TRAP-trunk pairings.

Evidence of synergistic roles between the LAT and back muscles have been established in trunk axial twist (Kumar, Narayan, & Zedka, 1996; McGill, 1991), flexion-extension (Callaghan, Gunning, & McGill, 1998), and lateral bending movements (Lavender et al., 1995; McGill, 1992). Correspondingly, there was a trend for the loose arm position to elicit the greatest cross-correlation coefficients in LAT-back pairings (primarily RLAT-back pairings) across most movements (Table 5). This trend potentially implies more co-activation between the LAT and back muscles in the loose arm position than in the crossed arm position. The LAT is involved with supporting multiple joints, contributing both a supporting shoulder moment as well as vertebral joint stability (McGill, 1992). The dynamic movement of the arm in the loose arm position may have required more co-activation between the LAT and back muscles to stabilize the shoulder joint and arm in order to facilitate a controlled movement. The exception to these trends, found for the LLAT-back pairings (greatest coefficients in either the loose or crossed position), may potentially be explained by the lack of involvement of the left LAT in right side rotation.

Anatomically, the LAT and back musculature are both on the posterior side of the body, while the LAT and abdominals are on opposite sides of the trunk. This positional and functional distinction could provide an explanation for why the general trends of arm position in LAT-abdominal pairings were much more variable than LAT-back pairings. The abdominal musculature is not only important in facilitating trunk movement, but also for stiffness and stability (Schinkel-Ivy & Drake, 2015a; Stokes, Gardner-Morse, & Henry, 2011). In the crossed arm position, humeral position and stability was maintained statically by the LAT. The abdominal musculature may have also contributed to maintaining stability within the spine. The need for co-activation between the LAT and abdominal musculature to maintain a stable trunk posture during the static crossed arm position may explain the trend of greater co-activation during the crossed arm position (relative to the other arm positions) in the RLAT-abdominals pairings in max-flex, as well as the LLAT-abdominals pairings in max-twist and max-bend.

Additional considerations are required to explain the remaining findings (Table 5). The one RLAT-abdominal pairing (RLAT-LEO) for which a difference was observed during max-twist (greater co-activation in the loose position) may have arisen from the roles of the contralateral EO and ipsilateral LAT muscles during trunk twisting (Kumar et al., 1996). The remaining trunk musculature plays a more secondary, stabilizing role in trunk twisting, and recruitment patterns have been reported to vary considerably between individuals (Kumar et al., 1996). This may provide an explanation for the lack of consistent trends for the pairings involving the primary mover RLAT and the secondary abdominal muscles (except LEO). The lack of trends in the LLAT-abdominal pairings during max-flex may have been dependent on whether the left or right arm was crossed over top, and whether individuals used the bottom arm to bear the weight of the top arm. Finally, during max-bend, the loose arm position elicited more co-activation than the crossed arm position in RLAT-abdominal pairings. McGill (1992) used an arm position analogous to the loose arm position and attributed ipsilateral LAT activity to stabilizing the shoulder during trunk lateral bending. A similar explanation could be used to explain the co-activation in RLAT-abdominals with a loose arm position, whereby increased co-activation stabilized the arm and shoulder joint as the trunk moved during max-bend (McGill, 1992).

The present study has implications in research, clinical, and workplace settings. The findings suggest that arm position may be an important consideration when designing experimental tasks in a research context, as arm position generally affected activation patterns. Clinically, altered trunk muscle activation patterns have been identified in individuals with LBP relative to healthy individuals (Nelson-Wong & Callaghan, 2010; Nelson-Wong et al., 2008, 2012, 2013). Altered patterns in the upper extremity musculature have also been identified in individuals with upper back and axioscapular impairments such as neck pain (Falla, Bilenkij, & Jull, 2004; Szeto, Straker, & O'Sullivan, 2005; Thorn et al., 2007), shoulder injuries (Chester, Smith, Hooper, & Dixon, 2010; Jaggi et al., 2012; Kibler et al., 2013; Ludewig & Reynolds, 2009; Paine & Voight, 2013), and limited scapular range of motion (Ludewig & Reynolds, 2009). This study examined interactions between muscles that are not typically examined simultaneously, which may ultimately contribute to the understanding of underlying mechanisms and resulting effects of pain and/or injury in the neck, axioscapular, or upper and lower back. Furthermore, these results represent a preliminary step in understanding and quantifying arm and trunk activation patterns in a young healthy population. Subsequently, future work may seek to determine the optimal level of co-activation in order to minimize the risk of pain (for example, from high levels of loading resulting from synchronized muscle activity) and maximize muscle efficiency (for example, from co-contraction patterns that produce the optimal amount of force for a specific movement). Upon identification of any altered arm and trunk activation patterns in symptomatic populations, and comparison of the same measures from a young healthy population, strategies may be developed to resolve those altered activation patterns. For example, determining the optimal level of co-activation between the trunk and arm musculature may be useful for retraining functional capacity or developing strategies to minimize trunk compression. On this foundation, clinicians may potentially develop exercises and interventions to rehabilitate altered activation patterns, reduce risk of re-injury, and return to work following back or shoulder injury.

Some methodological limitations arose in this study. The arm positions used throughout this study do not represent all possible arm positions. Alternative variations may include static and dynamic humeral elevations above 90° or trunk movements with no instructions regarding arm position. In addition, within the specified positions (crossed, abducted, loose), arm posture was not rigidly controlled (for example, the arm that was crossed over top in the crossed arm position). With respect to muscle selection, the TRAP and LAT muscles were used to represent the muscles that move the arm, although other muscles involved in shoulder movement may demonstrate different activation patterns relative to the trunk muscles (Dickerson, Hughes, & Chaffin, 2008; Palmerud et al., 1995). Furthermore, the electrode site for the upper-thoracic ES was such that the recordings may also have been influenced by the TRAP and LAT muscles, both of which overlie the upper-thoracic ES. However, the cross-correlation coefficient magnitudes of these muscle pairings were within the range of the remaining pairings for the majority of comparisons, and were generally of weak to moderate strength, suggesting that cross-talk was not present to a greater extent for the upper-thoracic ES pairings than for pairings involving the other trunk muscles. Lastly, the experimental population consisted of healthy young adults asymptomatic for LBP. It is unclear to what extent the findings of the present study will be applicable to an older population or to individuals symptomatic for low back, upper back/neck, or shoulder pain.

4.1. Conclusions

Arm position altered activation patterns between specific pairings of arm and trunk muscles during trunk ROM movements. The abducted arm position consistently elicited the greatest cross-correlation coefficients in the TRAP-trunk pairings during max-twist, while the arm position producing the greatest coefficients in the LAT-trunk pairings was more dependent on the trunk muscle (abdominal/back), the LAT muscle (left/right) and the specific movement involved in the pairing. Overall, this study contributes to an improved understanding of interactions in the musculature of the upper limbs and trunk, and the co-activation patterns required for different combinations of trunk and arm movements. These findings should be considered when designing experimental tasks in a research context, as arm positioning may contribute to altered activation patterns that may confound experimental results. Clinically, this study may have utility for comparison to symptomatic individuals with back or shoulder conditions, which may then aid in identifying the underlying mechanisms or contributing factors and facilitate the return to a healthy state. Along with future work, these findings may aid the development of practical methods for implementation in a clinical setting to address back and/or shoulder pain and injury.

Conflict of interest

None.

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