Transversus abdominis is part of a global not local muscle synergy during arm movement

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Abstract

The trunk muscle transversus abdominis (TrA) is thought to be controlled independently of the global trunk muscles. Methodological issues in the 1990s research such as unilateral electromyography and a limited range of arm movements justify a re-examination of this theory.

The hypothesis tested is that TrA bilateral co-contraction is a typical muscle synergy during arm movement. The activity of 6 pairs of trunk and lower limb muscles was recorded using bilateral electromyography during anticipatory postural adjustments (APAs) associated with the arm movements. The integrated APA electromyographical signals were analyzed for muscle synergy using Principle Component Analysis.

TrA does not typically bilaterally co-contract during arm movements (1 out of 6 participants did). APA muscle activity of all muscles during asymmetrical arm movements typically reflected a direction specific diagonal pattern incorporating a twisting motion to transfer energy from the ground up.

This finding is not consistent with the hypothesis that TrA plays a unique role providing bilateral, feed forward, multidirectional stiffening of the spine. This has significant implications to the theories underlying the role of TrA in back pain and in the training of isolated bilateral co-contraction of TrA in the prophylaxis of back pain.

Keywords: Anticipatory postural adjustments, abdominal muscles, postural control, trunk stability, low back pain

1.1. Introduction

The motor control of spinal stability has been a vital area of research in recent years. Spinal instability has been considered a critical factor in the development and maintenance of chronic low back pain (CLBP) with muscles accepted as the primary stabilizers of the spine {Panjabi, 1992 #630}{Solomonow, 2011 #2648}. However, disagreement exists as to which muscles are most important to spinal stability and how these muscles most effectively provide stability whilst the negative consequences of excessive muscle activity {Cholewicki, 2002 #939}{Grenier, 2007 #2412}Hodges, 2001 #260}{Brown, 2005 #2422}{Brown, 2005 #2293}{Brown, 2005 #682}. While muscle co-contraction clearly enhances spinal stability during lifting {van Dieen, 2003 #556} it is unclear how spinal stability can be maximized during ballistic movements. As {Hasan, 2005 #737} indicates, destabilization is a particular requirement of movement. A series of theories have been linked to address these issues. In particular, the concept of the local muscle system attempts to explain the provision of spinal stability while allowing movement through the global muscle system {Bergmark, 1989 #711}{Richardson, 1999 #709}. While a theory with some merit, the level of evidence supporting the theory of separate motor control of the local and global muscular systems is low.

The primary evidence supporting the concept of local versus global muscle systems in spinal systems comes through the investigation of the timing of the transversus abdominis (TrA) muscle in healthy people and in those with CLBP. The activation of TrA in healthy people was reported to be independent of the direction of the movement of the arm or perturbation to posture (Hodges, Cresswell, Daggfeldt, & Thorstensson, 2000; Hodges & Richardson, 1997). TrA was reported to activate regardless of the direction of the perturbation and operate through a separate control system (Richardson, et al., 1999). In subjects with CLBP, a delay in TrA activation was attributed to a fault in motor planning specifically associated with the local muscle system (Hodges, 2001). These aforementioned findings support the theory that TrA is a specific trunk stiffener. However methodological issues in these studies such as the use of unilateral electromyography (EMG) and the comparison of differing motor patterns – ipsilateral shoulder extension versus flexion (Hodges & Richardson, 1996; Richardson, et al., 1999) rendered the findings of these studies open to interpretation. In 2011, Morris and colleagues reported that the activity of TrA was not independent of the direction of arm movement. The current study adds to the findings of Morris, Lay and Allison (2011) by exploring the association of TrA with other groups of postural muscles to determine if it affords consideration as having a separate control system.

A centrally programmed diagonal postural pattern between postural segments has been reported during APAs associated with asymmetrical movements {Bouisset, 2000 #111}. The muscle synergies (muscles for which activity is highly correlated) during asymmetrical arm movement have been reported to be diagonal in the upper and lower limbs with bilateral co-activation in the trunk {Shiratori, 2004 #746}{Yamazaki, 2005 #701}. However, methodological issues may explain these findings since Shiratori and colleagues only considered the rectus abominis and the erector spinae and both groups used only surface electromyography {Shiratori, 2004 #746}{Yamazaki, 2005 #701}. The erector spinae and the rectus abdomini muscles are orientated along rather than across the body axis and as such may be less critical to counteracting the axial rotational forces due to asymmetrical arm movements. No unequivocal evidence of trunk muscle bilateral co-activation has been presented for asymmetrical arm movements.

The central aim of this paper is to re-examine the role of the transversus abdominis (TrA) during APAs associated with upper limb movements. Is TrA specialized to bilaterally co-contract to stiffen the trunk or does the activity of the TrA fit with a global diagonal pattern? The present study uses factor analysis on bilateral intramuscular electromyographic activity to determine if TrA acts independently from other muscles in the trunk and lower limb during APAs across a range of asymmetrical and symmetrical arm movements.

2.1. Materials and Methods

2.1.1. Participants

Seven healthy participants with no diagnosis of any pathological condition, no surgery to the trunk or abdomen, no history of serious injury to the shoulder or back, not using medication regularly, had not experienced pain requiring medical attention or which altered the activities of daily living for at least the past year and reported normal health at the time of testing. The full range of data was only available for 6 subjects since for 1 subject an EMG muscle channel was lost. The 7 participants had a mean age of 36 (standard deviation [SD] 6.3), height 172 of (SD 10.0) and mass of 71 (SD 17.9). Informed consent was obtained and the experiment was approved by The University of Western Australia's Human Research Ethics Committee in accordance with the ethical standards defined by the 1964 Declaration of Helsinki.

2.1.2. Data Collection

Participants performed 6 trials of each of 8 types of rapid arm movement (Figure 1) in a pseudo-randomized design. Starting position was arms held loosely at the side while standing comfortably and looking at the wall directly in front. It was suggested to subjects to raise the arm forwards between 45-60 degrees during practice but subjects selected their own amplitude during trials so as not to interfere in normal movement patterns. The order of performance of symmetrical weighted, asymmetrical, unilateral, bilateral and bilateral weighted movements was randomised for each subject. Within each movement with a right/left component the left/right order was alternated starting with the left movement. Weighted trials were performed with a 1 kg soft weight attached and grasped in each hand. A weight of 1 kg was selected in order to increase the torque experienced by the thorax without substantially altering the pattern of movement (Yamazaki et al. 2005). Participants had 10 practice trials for each task prior to the beginning of the experiment to ensure they were familiar with and could easily do the arm movements.

2.1.3. Electromyography

Surface electromyographic activity was recorded using 3 (per muscle) Ag/AgCl (Clear Trace ConMed, Utica, N.Y., USA) 38mm diameter circular electrodes, centers placed 2 cm apart on the following sites left and right lower internal oblique (SLIO, SRIO), erector spinae (SLES, SRES), biceps femoris (SLBF, SRBF) and on the anterior and posterior deltoids. SEMG data was collected using a Bagnoli 16 channel EMG system (Delsys Inc, Boston, MA, USA) using double differential electrode leads (CMRR 87dB at 60hz) (University of Western Australia – custom made) analogue filtered at 20 Hz to 450 Hz. A ground electrode (5 x 3 cm rectangular) was placed over the skin at the right clavicle. Surface EMG was amplified (x 100) and digitally sampled using a 16 bit AD card at 2000Hz.

Intramuscular electromyography (IEMG) was undertaken using bipolar intramuscular electrodes constructed from Nylon coated annealed stainless steel round wire (200µm). The coating was removed from the ends (1mm) and the tips were bent back as hooks of 2mm and 4mm length and threaded into a hypodermic needle (0.70 x 38mm). Prior to the insertion of intramuscular electrodes into the muscles, 2.5g of topical cream anesthetic (EMLA: (2.5% lidocaine, 2.5% prilocaine) was applied to the skin over the insertion site an hour before hand. Insertions were undertaken using ultrasound guidance (Toshiba Sonolayer SSA –270A) with a 5-MHz curved array sound head) between the anterior superior iliac spine and the ribcage (Figure 2). Intramuscular electrodes were inserted bilaterally into the TrA (ILTRA, IRTRA), internal oblique (ILIO, IRIO) and the external oblique (ILEO, IREO) all recorded at a site antero- laterally inferior to the ribs and superior to the ilium (Figure 2). Insertions were within 2 cm of each other at the surface but varied in depth from superficial (external oblique) to mid depth (internal oblique) to deepest (TrA). A ground electrode (5 x 3 cm rectangular) was placed over the skin at the left clavicle.

Intramuscular EMG data were amplified (x5000), analog filtered at 10-1000 Hz (Grass 7P511J amplifiers) and digitally sampled using a 16 bit AD card at 2000Hz (during arm movements).

All deltoid EMG signals were digitally band pass filtered at 20 – 450 Hz (Butterworth 2nd order, zero lag filter) then full wave rectified. Trunk and lower limb muscle EMG signals were band pass filtered at 100 – 450 Hz (Butterworth 2nd order, zero lag filter) then full wave rectified. 100 Hz was selected as the low band in order to eliminate contamination with heart rate artifact often evident in trunk muscle EMG.

Onset detection of deltoid signals was undertaken using the Integrated Protocol IP technique (Allison, 2003) applied over a time period of 500 ms before and 200ms after the peak of the EMG signal. Focal muscle onset (T_0) was considered to be the anterior deltoid muscle onset: (i) for the bilateral movement trials the earliest anterior deltoid onset, left or right; (ii) for unilateral trials to be the movement side anterior deltoid onset, and (iii) for asymmetrical trials, the anterior deltoid onset of the flexing side.

Depending on the muscle, up to 16% of trunk and lower limb EMG signal onsets occurred prior to 100 ms before the onset of deltoid. As a result of this finding, *APA muscle activity* was defined as the ∫EMG of the trunk or lower limb muscle from 150 before T_0 to 50 ms after T_0 (the APA window of 200ms) minus the baseline muscle activity for the trial (100ms x 2 =200 ms) (modified from Aruin and Latash, 1995). Baseline muscle activity amplitude was integrated from 425 ms to 325 ms before T_0.

2.1.4. Statistical Analysis

The Statistics package for Social Sciences (SPSS 14.0, SPSS Inc., Chicago, Illinois) was used to conduct a Factor analysis using Principle Component Analysis (PCA) with varimax rotation on the APA muscle activity of 6 pairs of trunk muscles (SLIO, SRIO, SLES, SRES, SLBF, SRBF, ILTRA, IRTRA, ILIO, IRIO, ILEO, IREO). Factor analysis uses patterns of correlations (colinearity) within a larger set of variables to identify variables that group together. Groupings with eigenvalues greater than one were accepted to represent a factor (muscle synergy). The factor loadings reflect the contribution of each variable to a factor. The factor scores reflect the contribution of each trial to a factor. Kaiser – Meyer – Olkin (KMO) measures of sampling adequacy and should be greater than 0.5. Barlett’s test of sphericity assesses the appropriateness of the sample to the analysis and significance should be less than 0.05. A 1 linear mixed model (SPSS 19.0, SPSS Inc., Chicago, Illinois) was used to compare factor loadings across arm movement type (subject = random). Estimated marginal means were used to clarify the relationship between factor score and movement type.

3.1. Results

PCA statistics listed in Table 1 demonstrated that sampling was adequate (KMO) and sphericity was acceptable indicating factor analysis was appropriate (Merkle, Layne, Bloomberg, & Zhang, 1998). Mean communalities for each muscle (across subjects) were greater than or equal to 0.71 (SD 0.163) indicating that all muscles contributed to the variance of the sample (Merkle, et al., 1998). Eigenvalues greater than 1 showed that the factor explained more variance than a single variable (Merkle, et al., 1998). For 4 out of the six participants 2 factors demonstrated eigenvalues greater than 1 while 2 participants had 3 factors with eigenvalues greater than 1.

Factor loadings were significantly different across the 8 arm movements for all 6 subjects for factor 1 (F=12.79, p<0.001) and factor 2 (F=8.22, p<0.001) indicating muscle patterns of activity were dependent on movement type. Post hoc analysis suggested that for most subjects the direction of arm movement was the controlling factor for pattern of muscle activity. Bilateral symmetrical arm movement trials (B and BW) did not contribute positively to factor 1 or 2 for most subjects (Figure 4).

Muscle synergies varied across the six subjects (Figure 3). For 5 out of the 6 subjects, TrA activity was more closely associated with a diagonal pattern of trunk and lower limb muscles activation than the contralateral TrA (Figure 3). The common muscle synergy for right arm movement was ILTRA, ILIO, IREO, SLIO, SLES and SRBF and vice versa for left arm movements. This diagonal pattern of muscle activation was demonstrated most clearly by subjects 1 and 2 for whom co-contraction of bilateral muscle pairs was less common than reciprocal action (Figure 3). Factor 1 for subjects 1, 2, 5 and 6 reflected the right arm movements (Figure 4). Factor 2 for subjects 1, 2 and 5 reflected the left arm movements (Figure 4). Factor 1 reflected the left arm raise pattern in subjects 3 and 4 (Figure 4). Subject 4 co-contacted left and right middle internal oblique (ILIO and IRIO) as part of the right arm raise pattern (red) (Figure 3). The right arm raise pattern was factor 2 for this subject (Figure 4). Subjects 5 and 6 demonstrated a more complicated pattern with 3 factors extracted (Figure 3). Subject 5 co-contracted the lower internal oblique (SLIO and SRIO) while subject 6 and subject 1 co-contracted the external obliques (ILEO and IREO). Subject 3 was the only participant who demonstrated co-contraction of the left and right transverses abdominis (ILTRA and IRTRA). Factor 2 (red) in this participant also included the left and right middle internal oblique (ILIO and IRIO) indicating a deep abdominal co-contraction muscle synergy (Figure 3). The co-contraction pattern for subject 3 was clearly related to both left and right arm movements and hence was independent of the direction of the axial rotation torque on the thorax (Factor 2 - Figure 4). However the bilateral arm movements were not included in factor 2 indicating that activation of the deep abdominal co-contraction muscle synergy was not independent of the direction of arm movement.

4.1. Discussion

This study is the first to demonstrate that the activation of each TrA muscle is more closely related to global muscles in a whole body diagonal pattern (Bouisset, et al., 2000) than to the contralateral TrA co-contraction pattern. It is important to note that patterns of muscle use did not follow stereotypical patterns for all subjects even though all subjects were healthy. It appears there is a natural variance in muscle use patterns which likely reflects different movement/stabilization strategies. The variability in patterns of abdominal muscle use observed in the current study may reflect differences in lumbar lordosis and consequent effects on the biomechanics of trunk rotation. The multi-segmental nature of the lumbar spine is likely to add degrees of freedom to potential movement patterns and result in variability across subjects in muscle activation. The clearest elements of a diagonal pattern were seen in the BF and TrA muscles. TrA formed part of this diagonal pattern of postural adjustments in the majority (5 out of 6) of subjects.

In their studies of APAs in standing, sitting and lying Van der Fits et al (1998) demonstrated that the relevant factor in the initiation of the pattern of APAs was the relative position of the support surface. Cordo & Nashner (1982) explained the sense of this suggesting that the most mechanically efficient method of compensating for the forces from the focal movement was to work from the support surface to the perturbation because the relative forces between segments were smaller. This ground up pattern can also be seen in the generation of torque during ballistic arm movements such as throwing. A throw uses the body segment linkage including a twisting motion to transfer energy from the ground up (McGill, Karpowicz, & Fenwick, 2009). Considering a rapid arm raise is a ballistic movement much like the throw, it is surprising that both Yamazaki et al. (2005) and Shiratori and Aruin (2004) reported that trunk muscles bilaterally co-activated during asymmetrical arm movements, suggestive of a firm trunk. However, these findings are open to interpretation since surface electromyography was used in the obliques with the consequent potential for crosstalk (Yamazaki, et al., 2005), the trunk muscles used were orientated vertically (e.g. rectus abdominis and the erector spinae) (Shiratori & Aruin, 2004) or the intramuscular measurements were unilateral (Richardson, et al., 1999). The current study utilized intramuscular electromyography and was able to demonstrate that the most common pattern of activation of the abdominal muscles during asymmetrical arm movement is asymmetrical rather than bilateral. The demonstration of asymmetrical and direction specific activity of TrA (using bilateral fine wire electromyography) in APAs prior to arm movement in (Morris, Lay, & Allison, 2011) is inconsistent with the previously proposed role of TrA in the multidirectional stiffening of the spine in healthy subjects (Hodges, 1999; Richardson, et al., 1999). The inclusion of TrA as part of a whole body pattern in APAs as seen in the current study is inconsistent with a proposed separate motor control pathway for the postural control of this muscle (Hodges, 2001).

Co-contraction of muscles rather than reciprocal action has been described as a less sophisticated strategy to stabilize posture during APAs associated with rapid asymmetrical movement (Schmitz, Martin, & Assaiante, 2002). Co-contraction, whilst effective at stabilizing joints, inhibits the flow of efficient movement. It would seem counterintuitive therefore to suggest that co-contraction of abdominal muscles is a sophisticated response to stabilize the trunk during activity where the goal is rapid movement. Trunk muscle co-contraction was observed in the current study in EO for 2 out of 6 subjects but only associated with the right arm (dominant arm) pattern (Figure 3 Subjects 1 and 6). Perhaps the balance between stabilizing joints and moving rapidly in dominant arm movements required some participants to utilize dual strategies and co-contract the trunk to some extent to protect the spine. The influence of arm dominance and pattern of postural muscle use requires further investigation. Co-contraction of global trunk muscles, particularly EO (O'Sullivan, 2000) is thought to be an adaptive technique in CLBP patients to minimize aggravation of symptoms by limiting trunk rotation (Ng, Richardson, Parnianpour, & Kippers, 2002). Ng et al. (2002) reported that CLBP patients may demonstrate an altered pattern of trunk muscle activity during trunk rotation. CLBP patients demonstrate more rigid and less variable kinematic pelvis/thorax coordination in the transverse plane during walking compared with healthy subjects (Lamoth, Daffertshofer, Meijer, & Beek, 2006; Lamoth, et al., 2002; Selles, Wagenaar, Smit, & Wuisman, 2001). Intramuscular insertion of the abdominal obliques is an invasive procedure and in some subjects may induce a response of bracing similar to that seen in CLBP. Subject 6 demonstrated relatively high levels of baseline TrA muscle activity relative to feed forward TrA activity (Morris, et al., 2011) and EO bilateral co-activation suggesting the adoption of a strategy for limiting the effects of movement on the trunk.

Constrained movement strategies have also been suggested to explain alterations in postural adjustments in CLBP patients (Moseley & Hodges, 2005). If the unilateral feed forward response of the TrA and IO contributed to spinal rotation, then a strategy to limit spinal rotation may be reflected in the delayed ipsilateral TrA activation reported in CLBP patients (Hodges & Richardson, 1996). Hodges and Richardson (1997) only reported muscle activity from the side contralateral to arm movement. The findings of the current study indicate that in left arm movements ipsilateral EO activates with IRTRA and IRIO to produce a diagonal pattern in the abdominal obliques. Had the ipsilateral muscles been reported by Hodges and Richardson (1997) ipsilateral EO likely would have also been delayed in CLBP patients. The delay in TrA in CLBP reported by Hodges and Richardson's (1997) may simply be a marker for a difference in movement strategy rather than a problem of local muscle control. Further investigation is required to test this hypothesis.

Subject 3 was the only subject to demonstrate a pattern of bilateral IO and TrA use despite a normal range of axial rotation torques on the thorax (Morris, et al., 2011). The pattern reflects a different strategy of trunk muscle use to the other subjects, one more consistent with the abdominal bracing taught by physiotherapists in the rehabilitation of CLBP. While a minority of subjects may use this strategy as a method of counteracting axial rotational torques on the thorax, it is appears to be unusual. The pattern was not independent of the direction of arm movement as bilateral (B) arm movements produced very little TrA activity on either side of the trunk. It may be advantageous to assess a larger group of individuals in order to ascertain the relative frequency of these patterns of trunk muscle use in the population.

Summary

TrA muscle activation reflects one element of the diagonal muscle synergy of muscle use associated with the efficient transfer of momentum from ground to hand. Bilateral co-contraction of TrA during asymmetrical arm movements is a rare motor pattern. The rationale for isolated co-contraction TrA training in the prophylaxis of CLBP needs reconsideration.

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Figure 1. The 8 arm movements from left to right: (1) asymmetrical shoulder flexion/extension – left forwards, right backwards with a 1 kg weight in each hand (AWL); (2) asymmetrical shoulder flexion/extension – left forwards, right backwards (AL); (3) Unilateral arm flexion – left (UL); (4) bilateral shoulder flexion i.e. both arms forwards (B); (5) bilateral shoulder flexion i.e. both arms forwards holding a 1 kg weight in each hand (BW); (6) Unilateral arm flexion – right (UR); (7) asymmetrical shoulder flexion/extension – right forwards, left backwards (AR) and (8) asymmetrical shoulder flexion/extension – right forwards, left backwards with a 1 kg weight in each hand (AWR).

Figure 2 A) The ultrasound guided insertion of intramuscular electrodes into EO - middle external oblique, IO - middle internal oblique and TrA - middle transversus abdominis. Note the electrodes were inserted bilaterally. Below the intramuscular insertions are the surface electrodes for lower internal oblique. B) The ultrasound screen output showing the muscle layers.

Figure 3. Radar Charts (1 for each subject) of the factor loadings for each muscle (n= 12) (PCA) for each of 6 subjects. Subjects 1, 2, 3 and 4 had two factors with eigenvalues greater than 1 and subjects 5 and 6 had three factors with eigenvalues greater than 1. The muscles are IRIO – middle right internal oblique, ILIO – middle left internal oblique, IRTRA – middle right transversus abdominis, ILTRA – middle left internal oblique, SRIO – lower right internal oblique, SLIO – lower left internal oblique, SRES – right erector spinae, SLES – left erector spinae, SRBF – right biceps femoris, SLBF – left biceps femoris, IREO – middle right external oblique, ILEO – middle left external oblique. Note for 5 out of the 6 participants ILTRA and IRTRA loaded on different factors – i.e. TrA did not co-contract bilaterally.

Figure 4. Area graph of mean factor scores (of 6 trials) for each subject for each of the 8 types of arm movements arranged in the order of predicated force on the thorax due to arm movement from left (left arm movements – anticlockwise force) to right (right arm movements – clockwise force). Each subject is a different colour. Factor 1 is on the left and factor 2 is on the right.

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Table 1. Statistics for the factor analysis (PCA)

Subject	1	2	3	4	5	6
Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO)	0.86	0.86	0.84	0.78	0.79	0.74
Bartlett's Test of Sphericity						
Approx. Chi-Square	686.775	875.543	712.580	595.587	834.184	564.005
df	66	66	66	66	66	66
sig.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
% variance explained						
factor 1	54	63	48	54	55	41
factor 1 and 2	76	82	84	76	74	67
factor 1, 2 and 3	-	-	-	-	87	81

Figure 1

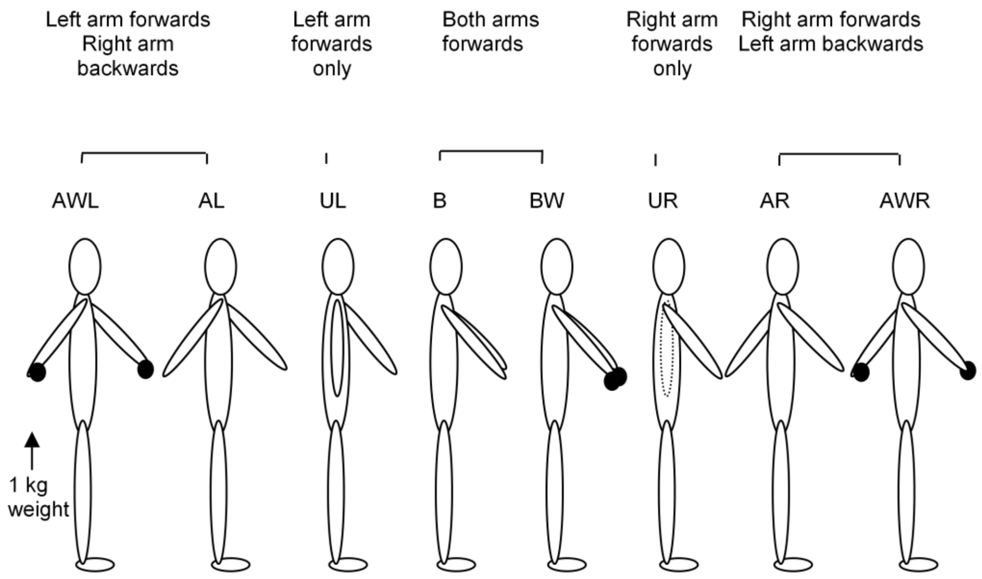

Figure 1

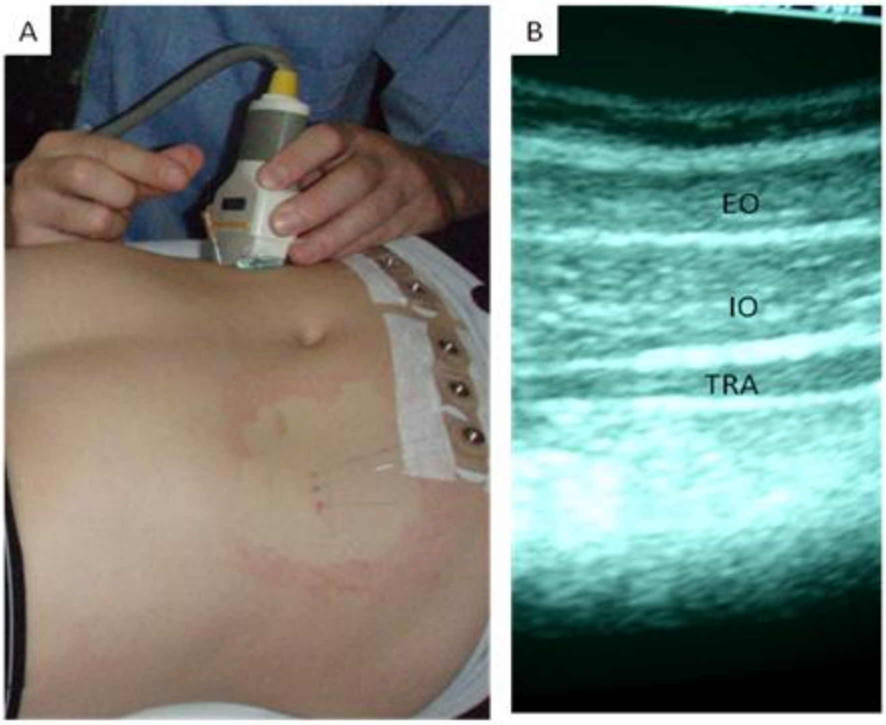

Figure 2

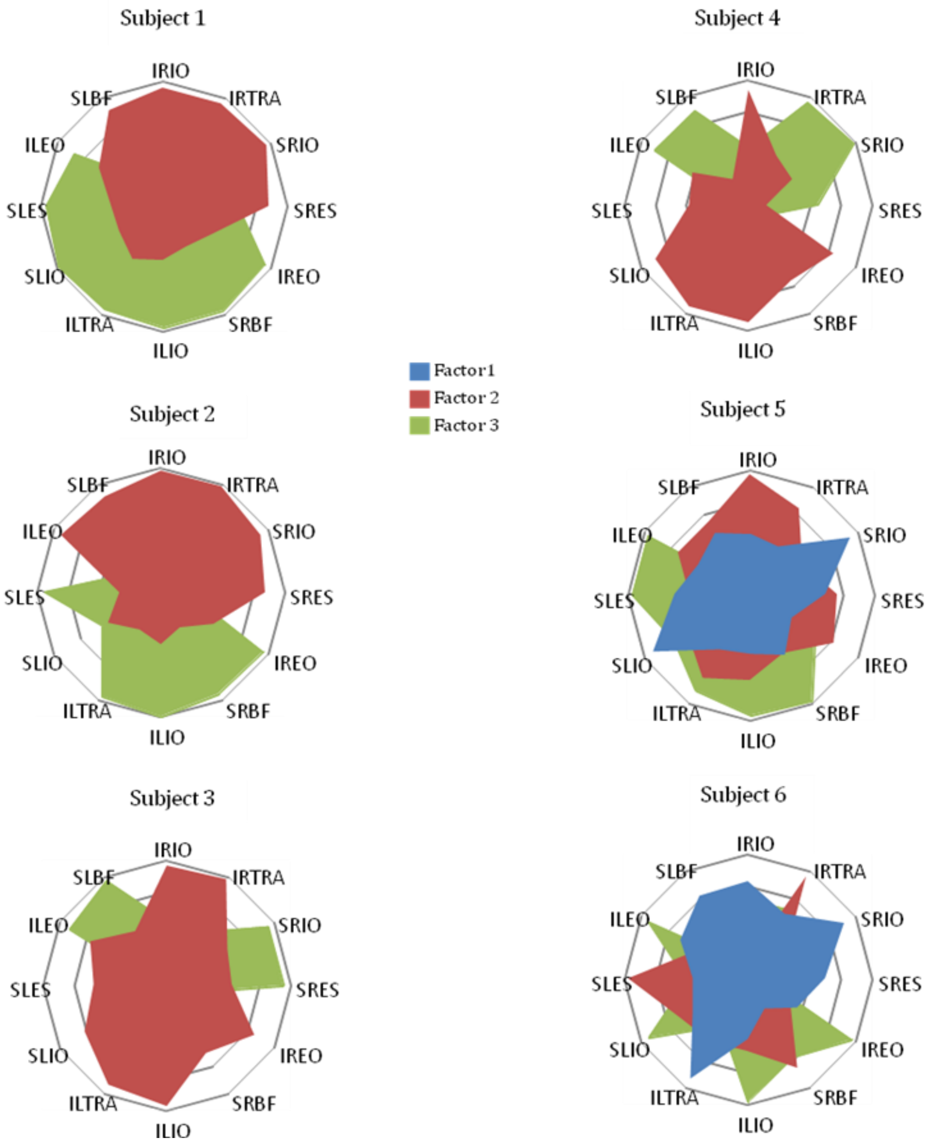
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Figure 3

Figure 4

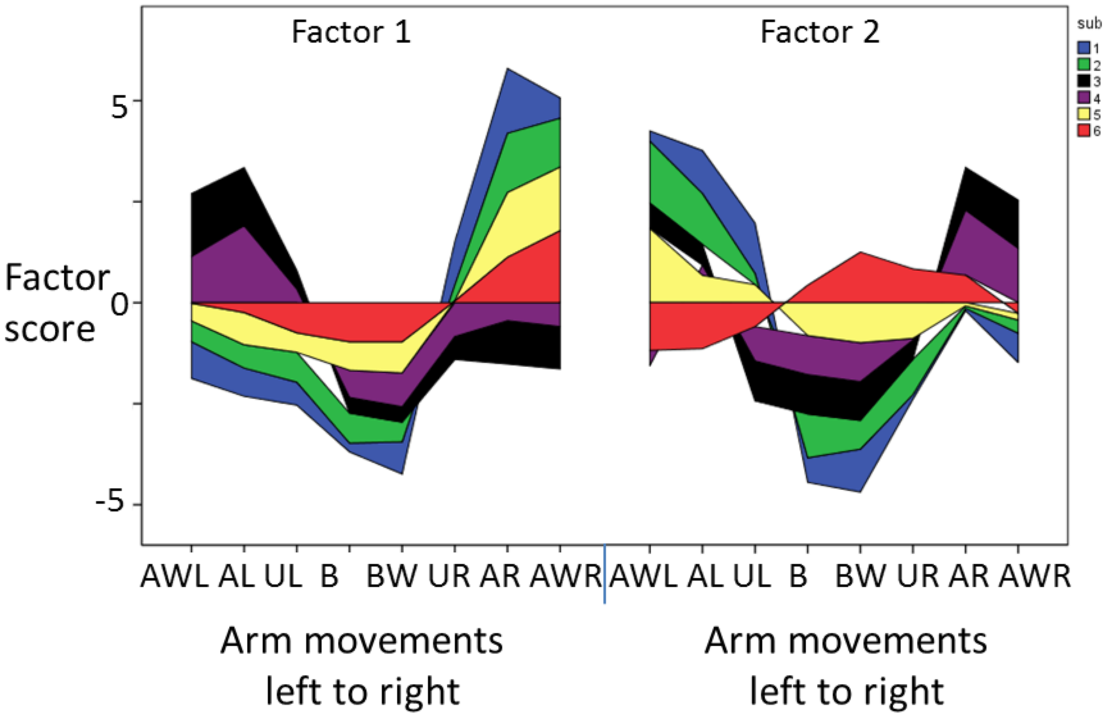

Figure 4