1-9-2020

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Published in final edited form as:
Gait Posture. 2020 February ; 76: 396–402. doi:10.1016/j.gaitpost.2020.01.003.

Task-invariance and reliability of anticipatory postural adjustments in healthy young adults

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Abstract

Background—Anticipatory postural adjustments (APAs) occur in the trunk during tasks such as rapid limb movement and are impaired in individuals with musculoskeletal and neurological dysfunction. To understand APA impairment, it is important to first determine if APAs can be measured reliably and which characteristics of APAs are task-invariant.

Research question—What is the test-retest reliability of latency, amplitude and muscle activation patterns (synergies) of trunk APAs during arm-raise and leg-raise tasks, and to what extent are these APA characteristics invariant across tasks at the individual and group levels?

Methods—15 young adults (mean age: 23.7 (±3.2) years) performed six trials of a rapid arm raise task in standing and a leg raise task in supine on two occasions. Latency, amplitude and coactivation of APAs in the erector spinae and external/internal oblique musculature were measured, and APA synergies were identified with principle components analysis. Test-retest reliability across the two sessions was calculated with intraclass correlation coefficients. Task-invariance was assessed at the individual level with correlation and at the group level with tests of equivalence.

Results—Most variables demonstrated acceptable test-retest reliability. Synergies and many features of APA activation varied across tasks, although at the individual level, motor performance time and amplitude of lumbar erector spinae activation were significantly correlated across tasks. Average pre-motor reaction time, external oblique latency, contralateral oblique amplitude and internal oblique coactivation were equivalent across tasks.

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AUTHOR CONTRIBUTIONS
Jo Armour Smith: Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Original Draft.
Niklas König Ignasiak: Formal Analysis, Writing - Review and Editing.
Jesse Jacobs: Conceptualization, Supervision, Writing – Review and Editing.

Conflict of interest statement:
None to declare. Jesse V. Jacobs is also employed by Liberty Mutual Insurance but this work was performed independent of that affiliation and this presents no conflict with the submitted study.

Significance—Characteristics of trunk muscle APAs quantified during a single task may not be representative of an anticipatory postural control strategy that generalizes across tasks. Therefore, APAs must be assessed during multiple tasks with varying biomechanical demands to adequately investigate mechanisms contributing to movement dysfunction. The reliability analysis in this study facilitates interpretation of group differences or changes in APA behavior in response to intervention for the selected tasks.

Keywords

Anticipatory postural adjustments; trunk; electromyography; muscle synergy

1. Introduction

Anticipatory postural adjustments (APAs) are an important component of postural control. During voluntary limb movements, the motion of the limbs induces reactive forces and rotatory torques in the trunk and pelvis[1,2]. These predictably destabilizing forces are counteracted by anticipatory activity in the abdominal and paraspinal muscles of the trunk.

Many studies that investigate APAs of the trunk utilize a single task to characterize APA behavior. As a result, it is unclear which APA characteristics are specific to the experimental task and which APA characteristics may form part of a postural control strategy that generalizes across tasks. Previous research suggests that some multi-muscle patterns of anticipatory activation, or “synergy” in the leg and trunk muscles, identified using principal components analysis, are invariant when the same task is performed with varying limb loading, limb movement direction, or support surface stability[3,4]. However, there is also evidence that the latency and amplitude of individual muscle activations within the synergy change in response to varying the speed of the limb movement and the postural set[5,6]. Therefore, a comparative evaluation of more distinct tasks is needed to understand the extent of task-invariance in APAs.

Rapid arm raising (RAR) is a common paradigm for investigating APAs. Recently, a supine leg raising (SLR) task has also been used to investigate trunk APAs and the neural mechanisms underlying them[7,8]. Although the biomechanical demands of raising an arm or leg are different, anticipatory activation of the trunk musculature is evident in both tasks[9,10]. The system of muscles within the trunk is highly redundant[11]. Therefore, there are multiple possible “solutions” for how anticipatory activity is distributed across trunk muscles to achieve the same postural goal. An individual may tend to utilize one solution more commonly than others[11]. Thus, a comparison of trunk APAs during the RAR and SLR tasks can establish if individuals demonstrate consistent trunk APA strategies across tasks utilizing different limbs and postural sets.

Despite the ubiquity of APA paradigms utilizing limb motion, there is limited evidence if trunk muscle APA characteristics can be measured reliably with these paradigms. The purpose of this study, therefore, was to first establish the test-retest reliability of the latency and amplitude of APAs in individual muscles and of the patterns of trunk muscle activation (synergies) for both tasks, and then to determine if subject-specific or group characteristics of trunk-muscle APAs are task-invariant across two contrasting limb motions. We hypothesized that the latency and amplitude of activation of individual muscles within the trunk muscle system would be task-dependent but that participants would demonstrate task-invariant patterns of coactivation and muscle synergy. We also hypothesized that participants would demonstrate task-invariant latency of the initiation of the APA.

2. Methods

2.1 Participants

Fifteen healthy adults (nine females; mean (± standard deviation) age 23.7 (±3.2) years; height 170.1 (±7.7) cm; mass 65.0 (±11.7) kg) participated. Participants were excluded if they had a history of low back pain. Sample size was determined by a power analysis that indicated power of 80% and effect size of 0.94 for detecting a significant difference in latency of abdominal muscle activation between the RAR and SLR tasks[12].

2.2 Instrumentation

Participants were instrumented with surface electromyography (EMG) electrodes using standard skin preparation and placement procedures per current guidelines[13]. Electrodes were positioned on the following muscles contralateral and ipsilateral to the side of the moving limb: thoracic erector spinae at the level of T10 (CTES, ITES), lumbar erector spinae at L4 (CLES, ILES), external oblique (CEO and IEO), and internal oblique (CIO and IIO) (interelectrode distance 20mm; Myotronics Inc, WA, USA). The anterior deltoid and rectus femoris muscles were instrumented on the side of the moving limb. EMG data were sampled at 1500Hz (Noraxon DTS sensors, Noraxon Inc, Scottsdale, USA).

2.3 Experimental tasks

For the RAR task, participants stood barefoot with their feet 10cm apart. In response to an auditory cue they flexed the arm as quickly as possible to above shoulder height (> 90°). For the SLR task, participants lay supine with their legs hip-distance apart and an adjustable bar fixed at a target height over the ankle malleoli. In response to the cue they lifted the leg up straight as quickly as possible to touch the bar. The height of the bar was set at half the length of the shank. Participants performed both tasks with their non-dominant limb. The non-dominant limb was chosen to slightly increase the difficulty of the tasks[14]. For each task, participants received a verbal explanation and then performed one, or if the first attempt was incorrect, two practice trials to ensure that the speed and amplitude of motion was correct[5,15]. They then performed six trials[16]. In each trial, the auditory cue was presented following a random foreperiod of 1000 to 4000 ms. Data were recorded and synchronized using Cortex software (Motion Analysis Corporation, Rohnert Park, USA).

2.4 Test-retest reliability

To assess the test-retest reliability of APA characteristics, the experimental procedures were repeated in the same order five to seven days after the initial data collection.

2.5 Data processing

Data were processed in MATLAB (MathWorks, Natick, USA). EMG data were corrected for DC offset and then band-pass filtered between 30 and 450Hz and full-wave rectified[17,18]. Task performance was quantified as: 1) pre-motor reaction time, which was the time from the cue to onset of EMG activation in the prime mover for the focal movement (deltoid for the RAR and rectus femoris for the SLR); 2) motor performance time, which was the time from onset of prime mover EMG activation to the end of the task. For the RAR, the end of the task was defined as the moment when the moving arm reached 90° of flexion, measured with a laser trigger system. For the SLR, the end of the task was defined as the moment when the moving leg reached the target height.

2.5.1 Latency of APAs—Latency of APA onset for each trunk muscle was quantified with the integrated profile method, an automatic method that has been described and validated elsewhere[19]. Latency of activation in each muscle was quantified relative to the onset of the prime mover for the focal movement. Muscle activation was classified as an APA if it occurred within a window 100ms before or 50ms after the onset of the prime mover[16]. For each muscle, the percentage of trials with onset in this anticipatory window was determined for both tasks and averaged across the group. In addition, the latency of APA initiation (latency of whichever muscle had the earliest activation relative to the prime mover) was calculated (Figure 1a & b).

2.5.2 Amplitude of APAs—Root-mean-squared amplitude of muscle activity in the APA window was calculated and normalized to average activity during 150ms of relaxed standing[20].

2.5.3 Spatial organization of APAs—The coactivation coefficient (CCI) was calculated for pairs of muscles. The CCI is the sum of normalized amplitude of activity for each muscle pair, weighted by the extent of coactivation. It is calculated with the equation;

$$\sum_{i=1}^{N} \left(\frac{EMG.low_i}{EMG.high_i} \right) \left(EMG.low_i + EMG.high_i \right)$$

N is the number of data points in the 150ms anticipatory window and *EMG.high* and *EMG.low* are the signals with the greatest and least amplitude at each time point[17]. Bilateral coactivation was calculated for the ipsilateral and contralateral sides of each muscle, and dorsal/ventral coactivation was determined between the average amplitude of the abdominal and paraspinal muscle groups.

Muscle synergies were identified with principal components analysis (PCA). First, an averaged waveform timeseries was calculated for each muscle that demonstrated APAs for at least 50% of trials in both tasks. This was the average of the normalized timeseries data in the anticipatory window across all repetitions of that task. This resulted in a N × P correlation matrix for each individual, such that N is 226 data points and P is the number of muscles. Data were checked to ensure that they met sampling adequacy and sphericity assumptions (>.5 on Kaiser-Meyer-Olkin Measure of Sampling Adequacy, $p < 0.001$ for

Bartlett's Test of Sphericity). Data were mean-centered and the principal components were extracted. Eigenvalues represent the amount of variance associated with each principal component (PC). Only PCs with eigenvalues greater than 1 were examined, and the amount of total variance explained by each PC was determined[21]. The factor loadings on each PC for each muscle were calculated using Varimax rotation[3,21]. Muscles with loading coefficients greater than 0.5 were considered as being significantly loaded onto that PC[3]. Across the group, the frequency that each muscle loaded onto each PC was calculated. The patterns of coactivation or reciprocal synergies evident in the PCs in each individual were examined and defined by the actions of the loaded muscles.

2.6 Statistical analyses

2.6.1 Test-retest reliability—Test-retest reliability across the two sessions was assessed using the intraclass correlation coefficient ($ICC_{2,\ 1,}$ absolute agreement). The standard error of the measurement (SEM) and minimal detectable change (MDC) were also calculated.

2.6.2 Task invariance – subject-specific—Pearson's correlation coefficients quantified the relationship between each participant's APA latency, APA amplitude and coactivation, and PC loading coefficient for each muscle across tasks. The relationship between rank order of each participant for these variables across tasks was determined with Spearman's correlation coefficient. Level of significance α was adjusted for multiple comparisons within each cluster of tests using a Bonferroni correction (α /n) (IBM SPSS Statistics version 25).

2.6.3 Task invariance – group—At the group level, similarities between tasks were quantified with equivalence tests using the Two One-Sided Tests (TOST) approach[22] (NCSS Statistical software). The TOST procedure tests if the 90% confidence interval of the difference between two measurements falls within a range of equivalence, defined *a priori* as plus or minus the MDC value calculated from the RAR test-retest reliability data. The p value for the equivalence test is the larger of the p values from the two one-sided tests. Level of significance α was adjusted for multiple comparisons using the modified Bonferroni correction for equivalence tests (α /n− 1)[23].

3. Results

Detectable activation during the APA window was evident in all the trunk muscles for the RAR task. For the SLR task, the thoracic paraspinal musculature were rarely activated (Figure 1c). In order to focus on muscles that made consistent contributions to the APA, analyses of reliability and task comparisons were only made for muscles that demonstrated detectable anticipatory onsets at least 50% of the time.

3.1 Test-retest reliability of task performance and APA characteristics

Test-retest reliability for metrics of task performance and APAs is shown in Table 1. Variables listed in bold font in the table demonstrated acceptable reliability (ICC greater than 0.6) and were retained for further analysis[24].

3.2 Subject specific task invariance

Correlations between tasks for task performance and reliable APA variables are shown in Table 2. Motor performance time and amplitude of CLES activity were significantly correlated across tasks at the Bonferroni-corrected level of significance (Figures 2a & b).

3.3 Group task invariance

Pre-motor reaction time was equivalent in both tasks (RAR = 0.229 (±0.052) s, SLR = 0.210 (±0.041) s; TOST equivalence test p = 0.006, adjusted $\alpha = 0.025$). Motor performance time was not equivalent (RAR = 0.225 (±0.031) s, SLR = 0.288 (±0.049) s: p = 0.999).

Onset latency for the muscles with acceptable reliability for both tasks is shown in Figure 3a. IEO latency was the same in the RAR and SLR tasks (TOST equivalence test p = 0.0085, adjusted $\alpha = 0.0125$). There was a trend toward CEO latency being the same for both tasks (p = 0.0245). The latency of CLES and IIO activation were not equivalent (p = 0.976 and p = 0.456 respectively). The latency of APA initiation was not the same in the two tasks (RAR −0.061(±0.023) s; SLR −0.049 (±0.017) s, p = 0.828).

Normalized amplitude of activity in CEO and CIO was the same in both tasks (TOST equivalence test p = 0.009 and p = 0.004 respectively, adjusted $\alpha = 0.010$). CLES amplitude was not equivalent (p = 0.999). The amount of IO coactivation was the same in both tasks (p = 0.009) but dorsal/ventral coactivation was not equivalent (p = 0.839) (Figure 3b).

3.4 Muscle synergies

All 15 participants had two PCs with eigenvalues greater than 1 for the RAR. For the SLR, 14 of the participants had one PC with an eigenvalue greater than 1, and one participant had two PCs. On average, the first two PCs accounted for 67.5 (±6.3)% of variance in the RAR task, and the first PC accounted for 64.4 (±5.9)% of variance for the SLR.

The frequency that each muscle loaded onto each PC across the group is shown in Figure 3c. For the RAR, CLES loaded onto PC 1 in most participants. This was combined with a reciprocal trunk rotation synergy involving one or both abdominals that rotate the trunk toward the moving arm (CEO and IIO) in five individuals (Figure 4a). In four individuals, PC1 combined CLES with an antagonist coactivation synergy, combining muscles that rotate the trunk in opposite directions (CEO & LEO, or LEO & LIO) (Figure 4b). The second PC for the RAR was predominantly IEO (n = 6) or CIO (n = 7).

For the SLR, IIO loaded on the first PC in 13 of the participants. This muscle functions in part to rotate the pelvis away from the moving leg. This was most commonly combined in an antagonist coactivation synergy with one or both of the muscles that rotate the pelvis toward the moving leg (IEO and CIO, n = 11) (Figure 4a & b).

3.4.1 Subject-specific task invariance – muscle synergies—There were no significant associations between the muscle loading coefficients for each participant between the RAR and the SLR (Table 2).

3.4.2 Group task invariance – muscle synergies—The frequency that a muscle loaded onto PC1 for the RAR and PC1 for the SLR approached significant equivalence for IIO ($p = 0.0234$, adjusted $\alpha = 0.0125$). For all other muscles, the frequency of loading was not equivalent across tasks (CLES $p = 0.8831$; CEO $p = 0.0876$; CIO $p = 0.3974$; IEO $p = 0.576$). There was no equivalence for the frequency that a muscle loaded onto PC2 for the RAR and PC1 for the SLR ($p > 0.05$ for all comparisons).

4. Discussion

This study establishes the reliability of quantifying trunk-muscle APAs and identifies APA characteristics that are task-invariant at the subject-specific and group level.

As expected, the varying biomechanical demands of the two focal limb movements resulted in modulation of APA latency and amplitude in specific muscles across tasks. Contrary to our original hypotheses, we found little evidence for task-invariance in muscle synergies. Additionally, there was no subject-specific tendency for earlier or later initiation of the APA that generalized across tasks. The only APA characteristic that was task-invariant for individuals was amplitude of activity in the contralateral lumbar erector spinae. Our findings contrast with existing research that demonstrated subject-specific muscle synergies in feedback postural responses with varying postural sets[25] and broad similarities in subject-specific usage of coactivation or reciprocal synergies across different versions of a load release task[3]. Taken together, these findings and the present study suggest that subject-specific task-invariant synergies may be recruited to respond rapidly to externally-induced perturbations, but that anticipated perturbations internally induced by voluntary movements may allow for pre-planning of APA solutions that are more specific to the task demands.

The lack of subject-specific task-invariance in the trunk musculature in this study may also be due to our study population. In healthy individuals, there are multiple patterns of trunk muscle activation available to maintain alignment and equilibrium during submaximal perturbations. Our findings suggest that healthy individuals do not employ the same temporal or spatial strategies within this redundant system for different tasks. It has been hypothesized that disordered postural control predisposes healthy individuals to future musculoskeletal dysfunction[26]. In order to adequately test this hypothesis, future research must assess an individual’s anticipatory postural control strategy across a range of tasks.

At the group level, some task-invariant characteristics emerged. Latency of onset in the IEO, amplitude of CEO and CIO activity, and coactivation of the bilateral internal obliques were the same during RAR and SLR. These abdominal APA characteristics may reflect a non-specific stiffening strategy for both tasks. Task-dependent characteristics were clearly related to the biomechanical demands of the focal limb movement and the postural context. The sagittal demand of RAR in standing[1,27] was met by earlier and greater amplitude of activation in the contralateral erector spinae, CLES loading onto the first PC in most individuals, and in increased coactivation between the dorsal and ventral musculature. Rotational torque on the trunk during the RAR[1] was counteracted with reciprocal synergies for rotation toward the moving arm in the first PC in most participants. In contrast, the first and only PC for SLR was very consistent across individuals and was characterized by abdominal coactivation that would counteract both the sagittal and rotational torques on the pelvis that occur during leg raising[2].

Our reliability analyses demonstrate that the performance of the focal movement for both tasks was consistent over time. Further, most EMG variables were reliably quantified in muscles that contribute consistently to the APA. To our knowledge studies that have previously investigated reliability of trunk muscle APAs only assessed latency during arm movement tasks[15,16,18]. Establishing the test-retest reliability and SEM for temporal, spatial, and amplitude characteristics of the APA facilitates the use and interpretation of these measures for group comparisons or tracking change over time.

Because this study investigated healthy participants, additional work utilizing multiple APA paradigms is needed to establish the extent of APA-task invariance in populations with clinical disorders that associate with modified anticipatory postural behavior[5,28–30]. Indeed, the extent of task-invariance itself may be an indicator of disrupted control. Additionally, because participants performed the tasks with their non-dominant limb, the study did not investigate any potential interaction between task-invariance and limb dominance.

Conclusion

APA characteristics for arm raising and for a novel leg raising paradigm can be reliably quantified in trunk muscles that consistently contribute to the APA. Only a small number of APA characteristics are task-invariant across these two contrasting limb motions.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1]. Hodges PW, Cresswell AG, Daggfeldt K, Thorstensson A, Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement, Gait Posture. 11 (2000) 92–101. doi: 10.1016/S0966-6362(99)00055-7. [PubMed: 10899662]

[2]. Hu H, Meijer OG, Hodges PW, Bruijn SM, Strijers RL, Nanayakkara PWB, van Royen BJ, Wu W, Xia C, van Dieën JH, Understanding the Active Straight Leg Raise (ASLR): An electromyographic study in healthy subjects, Man. Ther 17 (2012) 531–537. doi:10.1016/j.math.2012.05.010. [PubMed: 22728211]

[3]. Krishnamoorthy V, Latash ML, Scholz JP, Zatsiorsky VM, Muscle modes during shifts of the center of pressure by standing persons: Effect of instability and additional support, Exp. Brain Res. 157 (2004) 18–31. doi:10.1007/s00221-003-1812-y. [PubMed: 14985897]

[4]. Krishnamoorthy V, Goodman S, Zatsiorsky V, Latash ML, Muscle synergies during shifts of the center of pressure by standing persons: Identification of muscle modes, Biol. Cybern 89 (2003) 152–161. doi:10.1007/s00422-003-0419-5. [PubMed: 12905043]

[5]. Horak FB, Esselman P, Anderson ME, Lynch MK, The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals, J. Neurol. Neurosurg. Psychiatry 47 (1984) 1020–1028. doi:10.1136/jnnp.47.9.1020. [PubMed: 6481370]

[6]. Van Der Fits IBM, Klip AWJ, Van Eykern LA, Hadders-Algra M, Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults, Exp. Brain Res. 120 (1998) 202–216. doi:10.1007/s002210050394. [PubMed: 9629962]

[7]. de Lima-Pardini AC, de Azevedo Neto RM, Coelho DB, Boffino CC, Shergill SS, de Oliveira Souza C, Brant R, Barbosa ER, Cardoso EF, Teixeira LA, Cohen RG, Horak FB, Amaro E, An fMRI-compatible force measurement system for the evaluation of the neural correlates of step initiation, Sci. Rep 7 (2017) 43088. doi:10.1038/srep43088. [PubMed: 28230070]

[8]. Lomond KV, Jacobs JV, Hitt JR, Desarno MJ, Bunn JY, Henry SM, Effects of low back pain stabilization or movement system impairment treatments on voluntary postural adjustments: A randomized controlled trial, Spine J. 15 (2015) 596–606. doi:10.1016/j.spinee.2014.10.020. [PubMed: 25452017]

[9]. Allison GT, Henry SM, Allison T, Henry M, The influence of fatigue on trunk muscle responses to sudden arm movements, a pilot study, Exp. Brain Res. 17 (2002) 414–417. doi:10.1016/S0268-0033(02)00029-3.

[10]. Lomond KV, Henry SM, Jacobs JV, Hitt JR, Horak FB, Cohen RG, Schwartz D, Dumas JA, Naylor MR, Watts R, Desarno MJ, Protocol to assess the neurophysiology associated with multi-segmental postural coordination, Physiol. Meas 34 (2013). doi:10.1088/0967-3334/34/10/N97.

[11]. Hodges PW, Coppieters MW, MacDonald D, Cholewicki J, New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches, Eur. J. Pain (United Kingdom). 17 (2013) 1138–1146. doi:10.1002/j.1532-2149.2013.00286.x.

[12]. Massé-Alarie H, Beaulieu LD, Preuss R, Schneider C, Task-specificity of bilateral anticipatory activation of the deep abdominal muscles in healthy and chronic low back pain populations, Gait Posture. 41 (2015) 440–447. doi:10.1016/j.gaitpost.2014.11.006. [PubMed: 25482033]

[13]. Hermens HJ, Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol Development of recommendations for SEMG sensors and sensor placement procedures, J. Electromyogr. Kinesiol. Off. J. Int. Soc. Electrophysiol. Kinesiol 10 (2000) 361–374. doi:10.1016/S1050-6411(00)00027-4.

[14]. Bussey MD, de Castro MP, Aldabe D, Shemmell J, Sex differences in anticipatory postural adjustments during rapid single leg lift, Hum. Mov. Sci 57 (2017) 417–425. doi:10.1016/j.humov.2017.10.003. [PubMed: 29054327]

[15]. Marshall P, Murphy B, The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement, J. Electromyogr. Kinesiol 13 (2003) 477–489. doi:10.1016/S1050-6411(03)00027-0. [PubMed: 12932422]

[16]. Mehta R, Cannella M, Henry SM, Smith S, Giszter S, Silfies SP, Trunk Postural Muscle Timing Is Not Compromised In Low Back Pain Patients Clinically Diagnosed With Movement Coordination Impairments, Motor Control. 21 (2017) 133–157. doi:10.1123/mc.2015-0049. [PubMed: 26623551]

[17]. Nelson-Wong E, Callaghan JP, Is muscle co-activation a predisposing factor for low back pain development during standing? A multifactorial approach for early identification of at-risk individuals, J. Electromyogr. Kinesiol 20 (2010) 256–263. doi:10.1016/j.jelekin.2009.04.009. [PubMed: 19467607]

[18]. Boucher JA, Preuss R, Henry SM, Nugent M, Larivière C, Trunk postural adjustments: Medium-term reliability and correlation with changes of clinical outcomes following an 8-week lumbar stabilization exercise program, J. Electromyogr. Kinesiol 41 (2018) 66–76. doi:10.1016/j.jelekin.2018.04.006. [PubMed: 29777980]

[19]. Allison GT, Trunk muscle onset detection technique for EMG signals with ECG artefact, J. Electromyogr. Kinesiol 13 (2003) 209–216. doi:10.1016/S1050-6411(03)00019-1. [PubMed: 12706601]

[20]. Aruin AS, Latash ML, Direction specificity of the postural muscules in feed-forward postural reaction during fast voluntary arm movements, Exp. Brain. Res 103 (1995) 323–332. doi:10.1007/BF00231718. [PubMed: 7789439]

[21]. Asaka T, Wang Y, Feedforward postural muscle modes and multi-mode coordination in mild cerebellar ataxia, Exp. Brain Res. 210 (2011) 153–163. doi:10.1007/s00221-011-2613-3. [PubMed: 21390487]

[22]. Schuirmann DJ, A comparison of the Two One-Sided Tests Procedures and the Power Approach for assessing the equivalence of average bioavailability, J. Pharmocokinetics Biopharm. 15 (1987) 657–680.

[23]. Lauzon C, Caffo B, Easy Multiplicity Control in Equivalence Testing Using Two One-sided Tests, Am. Stat 63 (2009) 147–154. doi:10.1198/tast.2009.0029.Easy. [PubMed: 20046823]

[24]. Cicchetti DV, Guidelines, Criteria, and Rules of Thumb for Evaluating Normed and Standardized Assessment Instruments in Psychology, Psychol. Assess 6 (1994) 284–290. doi: 10.1037/1040-3590.6.4.284.

[25]. Torres-Oviedo G, Ting LH, Subject-Specific Muscle Synergies in Human Balance Control Are Consistent Across Different Biomechanical Contexts, J. Neurophysiol 103 (2010) 3084–3098. doi:10.1152/jn.00960.2009. [PubMed: 20393070]

[26]. Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, Goldberg B, Delayed Trunk Muscle Reflex Responses Increase the Risk of Low Back Injuries, Spine (Phila. Pa. 1976). 30 (2005) 2614–2620. doi:10.1097/01.brs.0000188273.27463.bc. [PubMed: 16319747]

[27]. Friedli WG, Cohen L, Hallett M, Stanhope S, Simon SR, Postural adjustments associated with rapid voluntary arm movements. II. Biochemical analysis, J. Neurol. Neurosurg. Psychiatry 51 (1988) 232–243. doi:10.1136/jnnp.51.2.232. [PubMed: 3346688]

[28]. Smith JA, Fisher BE, Anticipatory postural adjustments and spatial organization of motor cortex: evidence of adaptive compensations in healthy older adults, J. Neurophysiol (2019) 2796–2805. doi:10.1152/jn.00428.2018.

[29]. Jacobs JV, Lyman CA, Hitt JR, Henry SM, Task-related and person-related variables influence the effect of low back pain on anticipatory postural adjustments, Hum. Mov. Sci 54 (2017) 210–219. doi:10.1016/j.humov.2017.05.007. [PubMed: 28527423]

[30]. V Jacobs J, Lou J, a Kraakevik J, Horak FB, The supplementary motor area contributes to the timing of the anticipatory postrual adjustment during step initiation in participants with and without Parkinson’s diseaseic Access, Neuroscience. 164 (2009) 877–885. doi:10.1016/j.neuroscience.2009.08.002.The. [PubMed: 19665521]

HIGHLIGHTS

Test-retest reliability was acceptable for most trunk APA characteristics

Individuals had task-invariant motor performance time and paraspinal muscle amplitude

Patterns of muscle synergies were largely task-dependent

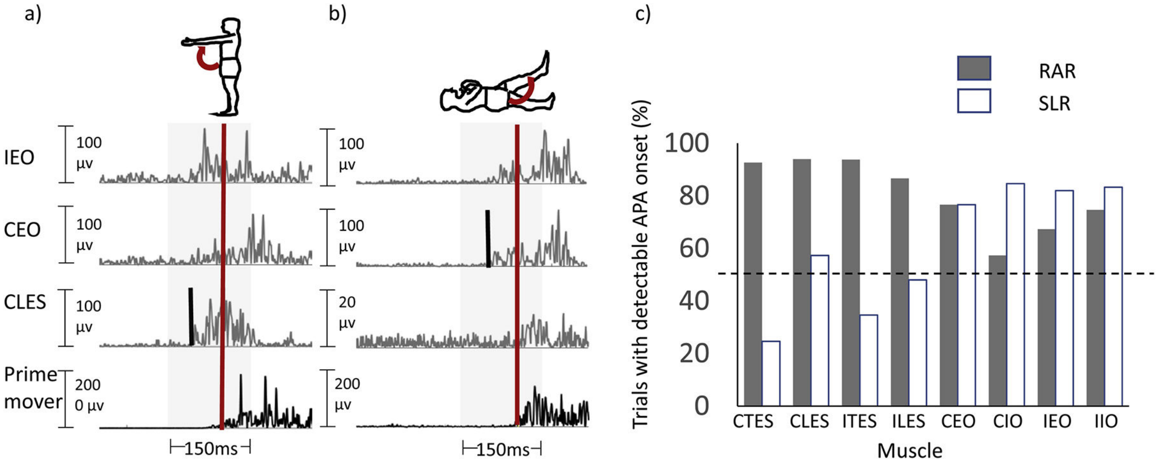

Figure 1.

Representative individual data showing rectified EMG during a) the rapid arm raise (RAR) task and b) the supine leg raise (SLR) task. Onset of activation of the prime mover (deltoid for RAR and rectus femoris for SLR) is indicated by the red line. The 150ms APA window is shaded in gray. The timing of the initiation of the APA is indicated by the black line identifying the earliest muscle activation (in the contralateral erector spinae, CLES, for the RAR and the contralateral external oblique, CEO, for the SLR). c) Percentage of trials with detectable anticipatory onsets in both tasks. Dotted line indicates 50%.

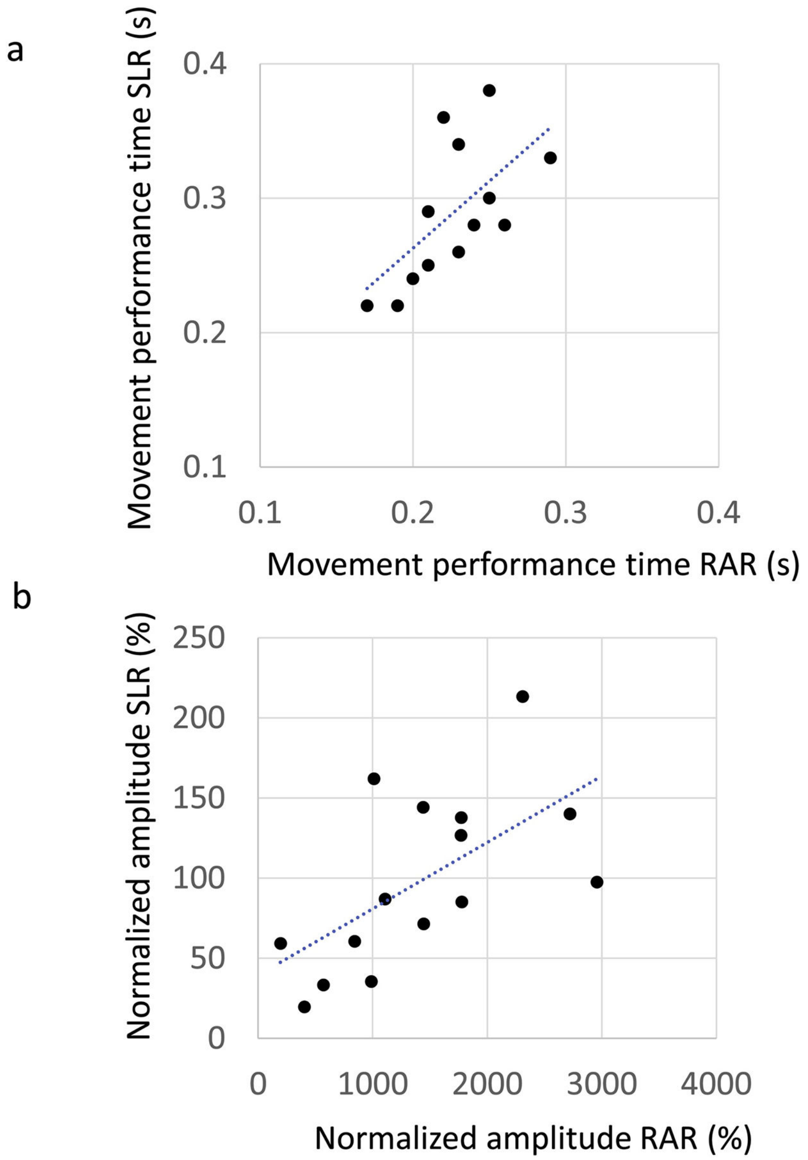

Figure 2.

Subject-specific task invariance. a) Movement performance time for the rapid arm raise (RAR) and leg raise (SLR). b) Amplitude of activity in the contralateral lumbar paraspinal (CLES) for the RAR versus SLR tasks.

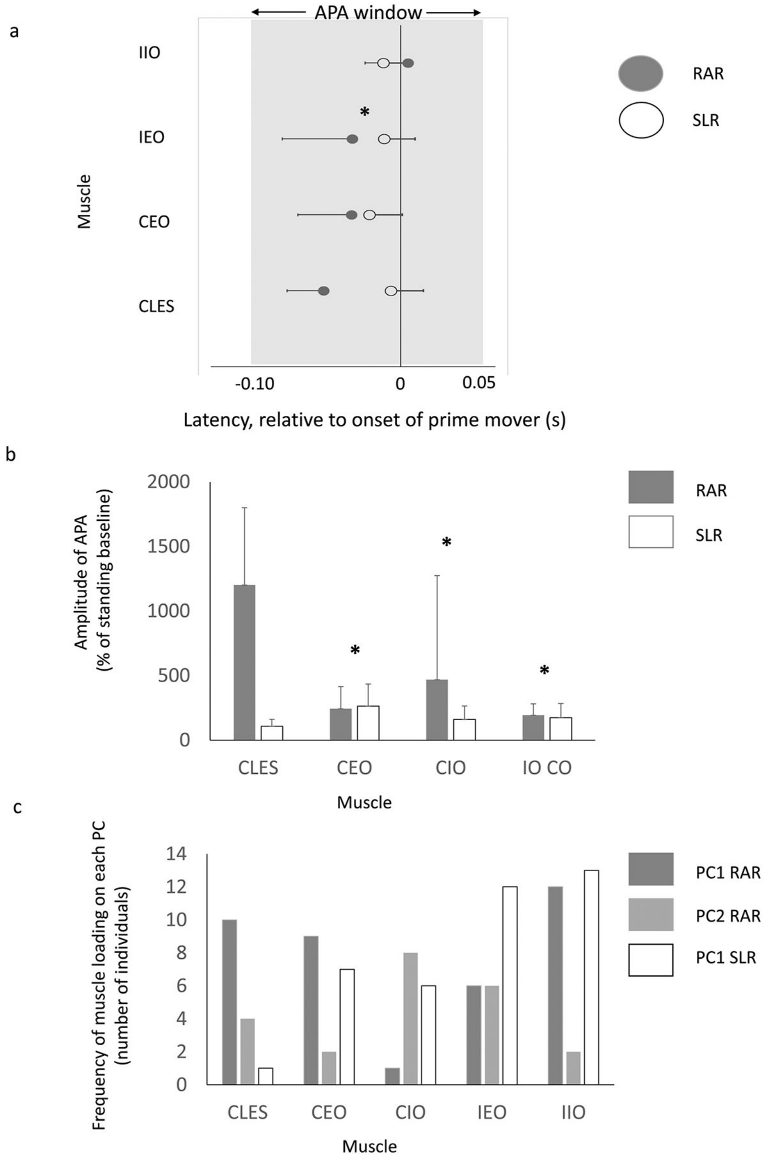

Figure 3.

Task invariance at the group level. Variables that reached the statistical level of significance for the equivalence tests, indicating that they are the same across tasks, are shown with an asterisk: a) Latency of onset for muscles with reliable anticipatory activation in both tasks relative to onset of prime mover; b) Amplitude of activity and coactivation in the anticipatory window c) Frequency that each muscle loaded onto the first and second principal components (PC) for the rapid arm raise (RAR) and first principal component for the leg raise (SLR).

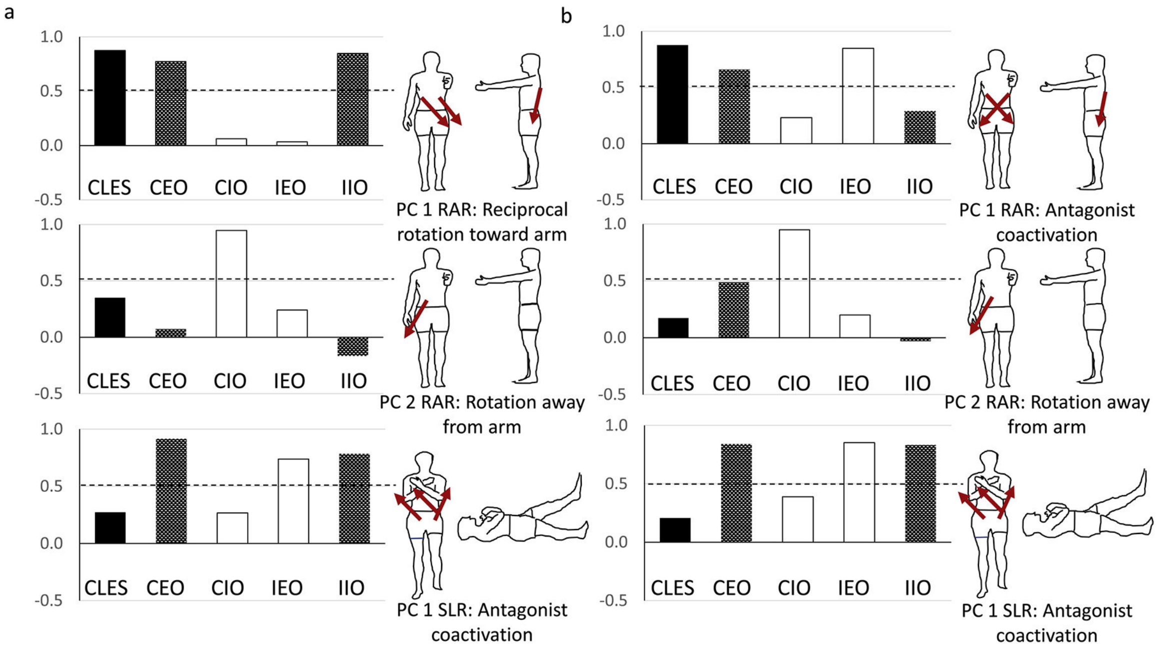

Figure 4.

Data from two representative individuals are shown. a) Individual with reciprocal rotation strategy toward the moving arm combined with trunk extension for PC 1 of the rapid arm raise (RAR). b) Individual with an antagonist coactivation strategy combined with trunk extension for PC 1 of the rapid arm raise. Coefficients for muscle loading on the first (top) and second (middle) principal components (PC) for the rapid arm raise and first (bottom) principal component for the leg raise (SLR). Muscles with a coefficient greater than 0.5 are loaded on that PC.

Table 1.

Intraclass correlation coefficients and standard error of measurement (SEM)

		ICC	SEM*
Rapid Arm Raise			
	Pre-motor reaction time	**0.74**	0.02
	Motor performance time	**0.92**	0.01
	CTES onset	**0.88**	0.01
	CLES onset	**0.76**	0.01
	ITES onset	**0.72**	0.01
	ILES onset	**0.60**	0.01
	CEO onset	**0.74**	0.01
	CIO onset	0.57	0.02
	IEO onset	**0.68**	0.02
	IIO onset	**0.96**	0.01
	CTES amplitude	0.42	728.28
	CLES amplitude	**0.87**	193.54
	ITES amplitude	0.40	865.83
	ILES amplitude	**0.66**	247.55
	CEO amplitude	**0.61**	97.64
	CIO amplitude	**0.91**	188.37
	IEO amplitude	**0.71**	111.38
	IIO amplitude	0.50	55.65
	TES coactivation	**0.79**	215.90
	LES coactivation	**0.73**	273.96
	EO coactivation	**0.82**	60.10
	IO coactivation	**0.69**	36.48
	Dorsal-ventral coactivation	**0.89**	351.17
	Variance PC 1	0.35	6.34
	Variance PC 2	0.16	4.16
	Frequency of loading PC 1	**0.62**	2.02
	Frequency of loading PC 2	**0.70**	1.63
Supine Leg Raise			
	Pre-motor reaction time	**0.65**	0.02
	Motor performance time	**0.60**	0.03
	CLES onset	**0.74**	0.02
	CEO onset	**0.94**	0.01
	CIO onset	**0.81**	0.01
	IEO onset	**0.78**	0.01
	IIO onset	**0.60**	0.01
	CLES amplitude	**0.77**	32.26
	CEO amplitude	**0.70**	136.91
	CIO amplitude	**0.75**	49.02

		ICC	**SEM***
	IEO amplitude	0.04	266.41
	IIO amplitude	0.00	621.83
	EO coactivation	0.42	186.72
	IO coactivation	**0.80**	42.61
	Dorsal-ventral coactivation	**0.70**	183.73
	Variance PC 1	**0.60**	5.84
	Frequency of loading PC 1	**0.93**	1.11

Units for SEM are in s (reaction/motor performance time and APA onset), % of baseline (APA amplitude and co-contraction), % (PC variance)

Table 2.

Linear and rank correlations for reliable APA characteristics

	Linear correlation	Rank correlation
Task performance		
Pre-motor reaction time	0.092	−0.036
Motor performance time	0.627 [*]	0.692 [*]
APA latency		
CLES	0.194	0.319
CEO	−0.148	−0.033
IEO	0.283	0.270
IIO	−0.042	−0.125
APA initiation	−0.218	−0.142
APA amplitude		
CLES	0.688 [†]	0.729 [†]
CEO	−0.051	0.204
CIO	0.475	−0.036
Dorsal/ventral CoA	0.182	−0.221
IO CoA	0.167	0.193
Muscle loading on PC1 RAR and PC1 SLR		
CLES	−0.304	0.068
CEO	−0.146	−0.318
CIO	−0.322	−0.243
IEO	−0.190	−0.057
IIO	−0.333	−0.375
Muscle loading on PC2 RAR and PC1 SLR		
CLES	0.545	0.507
CEO	−0.160	−0.061
CIO	−0.133	−0.046
IEO	0.200	0.175
IIO	0.399	0.482

Significant correlation at Bonferroni-corrected level of α:

[*] $p < 0.025$,

[†] $p < 0.01$