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Sex differences in anticipatory postural adjustments during rapid single leg lift

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ABSTRACT

The aim of this study was to assess the influence of sex on the kinetic, kinematic and neuromuscular correlates of anticipatory postural adjustments (APAs) during a single leg lift task performed by healthy participants. Fifty healthy age and body mass index matched participants (25 women and 25 men) performed 20 single leg lift task (hip flexion to 90° as quickly as possible) with their dominant and their non-dominant lower limbs. A force plate was used to determine the medial-lateral displacement of the center of pressure (COP_{ML}), and the initiation of weight shift (T_0); kinematics was used to determine leg lift (T_1); and electromyography was used to determine onset times from eight muscles: bilateral external oblique, internal oblique and lumbar multifidus, and unilateral (stance limb) gluteus maximus and biceps femoris. Movement control limb dominance was included in the analysis. Statistically significant interactions between sex and limb dominance ($p < .001$) were observed for T_1, $COP_{ML,}$ and muscle onsets. Also, statistically significant main effect of sex on T_0 was observed. Women showed increased APA time (T_1) and magnitude (COP_{ML}) in their dominant limbs compared to men. Such differences between sexes did not occur in the non-dominant limb. Women recruited proximal muscles later than their man counterparts. Overall, women appear to have a stronger effect of limb dominance on their anticipatory postural control strategy which requires further investigation. The findings of the current study indicate that women and men differ in their anticipatory postural control strategy for rapid single leg lift.

1. Introduction

The prevalence of low back pain (Schneider, Randoll, & Buchner, 2006), and the frequency and duration of musculoskeletal pain (Berkley, 1997; Leveille, Zhang, McMullen, Kelly-Hayes, & Felson, 2005; Unruh, 1996) are greater in women than men. While social and psychological factors appear to play a role in the sex-specific concentrations of musculoskeletal disorders (Wijnhoven, de Vet, & Picavet, 2006), the importance of those factors can only be understood once the contributions of biophysical mechanisms have been established. The biophysical characteristic most commonly linked with low back pain is suboptimal stabilization of the lumbar spine, which has been associated with delayed trunk muscle activation during dynamic stability tasks (Hodges & Richardson, 1996). The activation of trunk muscles to stabilize the spine often occurs in advance of limb or whole-body movements that would otherwise destabilize spinal posture (Bussey & Milosavljevic, 2015; Hungerford, Gilleard, & Hodges, 2003), this phenomenon is an example of

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feed-forward postural control. Impairments of anticipatory trunk muscle actions may therefore be an important factor in the development of low back pain (Moseley, Nicholas, & Hodges, 2004). Despite the higher prevalence of low back pain in women and the association between low back pain and muscular activation delays, sex-specific characteristics are usually not considered in studies exploring feed-forward mechanisms of postural control (Cau et al., 2014; Hall, Brauer, Horak, & Hodges, 2010; Halliday, Winter, Frank, Patla, & Prince, 1998; Maribo, Stengaard-Pedersen, Jensen, Andersen, & Schiøttz-Christensen, 2011; Mehta, Cannella, Smith, & Silfies, 2010). The identification of sex-specific features in postural control strategy during self-initiated perturbations may help us understand the greater vulnerability of women to musculoskeletal disorders in general and low back pain in particular. For example, a greater reliance by women on feedback associated to decreased feed-forward control during static to dynamic balance transitions might expose them to greater risk of injury in the event of sensorial dysfunction induced or pregnancy, aging or other factors.

The ability of the human sensorimotor system to predict and compensate for self-initiated perturbations becomes particularly important during transitions from a standing posture to dynamic activities, such as walking or single leg lift. These actions require a complex cascade of mechanical and neuromuscular events that must be timed to ensure that the transition takes place without loss of balance (Cau et al., 2014; Hungerford et al., 2003). Since the desired changes in limb and body position have consequences for balance, the neuromuscular events necessary to ensure proper postural control and smooth load transfer between lower limbs and spine require motor commands to be delivered both with and without feedback-based regulation (Friedli, Hallett, & Simon, 1984; Krishnan, Aruin, & Latash, 2011; Latash, 2010). Anticipatory postural adjustments (APAs) are automatic actions of the neuromuscular system that occur in order to minimize the destabilizing effect of voluntary movements on limb or whole body posture. To achieve this, APAs must be initiated before sensory feedback is available about segmental motion or postural perturbation (feed-forward control) (Hugon, Massion, & Wiesendanger, 1982). Individuals' knowledge about several factors related to the task, such as the magnitude, direction and type of the perturbation, as well as instructional or mechanical constraints on posture, influence the output from feed-forward and feedback control networks (Ito, Azuma, & Yamashita, 2003; Latash, 2010). Given the association between delays in feed forward control and low back pain (Hodges & Richardson, 1996), APAs generated prior to single leg lifts provide an excellent model for detecting differences in feed forward trunk and pelvic girdle control between men and women.

Unlike many upper limb tasks, self-initiated lower limb tasks typically involve either whole body progression (e.g., during step initiation) or a transitory base of support (e.g., during single hip flexion). As such APAs may not be wholly dedicated to the focal movement but also to the postural chain (Bouisset & Do, 2008; Yiou, Ditcharles, & Le Bozec, 2011). During rapid hip flexion, the APA phase is marked by an initial weight shift toward the swing leg, observed as a posterior lateral shift in the center of pressure (Hass, Waddell, Fleming, Juncos, & Gregor, 2005; Hass et al., 2004). This initial load transfer is considered a postural chain response and the associated trunk muscle activity has been identified as clinically relevant for stabilizing the lumbopelvic complex in preparation for movement (Hodges & Richardson, 1998; Hungerford et al., 2003; Sims & Brauer, 2000; Stokes, Gardner-Morse, & Henry, 2011). Particularly, activity in the multifidus, transverse abdominis, internal and external oblique has been identified as critical to the stability of the lumbopelvic complex prior to and during the load transfer phase of rapid hip flexion movements (Hungerford et al., 2003; Stokes et al., 2011).

The aim of this study was to assess the influence of sex on the kinetic, kinematic and neuromuscular correlates of APAs during a single leg lift task performed by healthy participants. Since women are more susceptible to types of pain associated with suboptimal feed-forward control of trunk and pelvic girdle muscles (P W Hodges & Richardson, 1998; Schneider et al., 2006; Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008), we predicted that when women perform a single leg lift task they would demonstrate delays in feed-forward activation of those muscles. Thus, we hypothesized that the initiation of weight shift, leg lift and muscle onsets would occur later in women, as such women would have delayed muscle activation and longer APA duration compared to men.

2. Methods

2.1. Participants

Fifty healthy age and body mass index matched participants (Table 1) gave informed consent to take part in this study (University of Otago Human Ethics Committee #12/188). Participants were excluded from the study if they had history of low back or pelvic girdle pain, a known localized spinal pathology, a history of spinal fracture, disc rupture, spinal surgery, diagnosed spinal deformity or instability, known congenital anomalies of the hip, pelvis or spine, known systemic arthropathy or neuropathy, diagnosed acute disk herniation/prolapse, pregnancy or less than six months postpartum, recent lower limb injury or surgery or the presence of any

Table 1
Participant demographics.

	Men (n = 25)	Women (n = 25)	p-value
Age [years]	27.1 SD 6.6	29.5 SD 9.1	.306
Height [m]	176.1 SD 7.1	166.2 SD 7.5	< .001
Mass [kg]	74.8 SD 9.0	65.0 SD 10.2	< .001
Body mass index [kg/m^2]	24.1 SD 2.2	23.5 SD 3.2	.457
Limb dominance [right/left]	25/0	25/0	n/a

other known musculoskeletal red flags.

2.2. Equipment

Ten Vicon© MX T20 cameras were used to collect three-dimensional kinematics of the trunk, pelvis and lower limbs at 100 Hz using a fifty-two retroreflective marker model, although, only the two calcaneal markers (from each foot) were extracted for analysis. Electrical activity of the muscles was recorded from the external oblique (EO), transverse abdominis/internal oblique (IO), lumbar multifidus (MF), gluteus maximus (GM) and biceps femoris (BF) using an 8 channel telemetry EMG (Noraxon Telemyo 900, Noraxon USA Inc.) collecting at 1000 Hz. Activity from the GM and BF were collected from the stance limb only (i.e., contralateral to swing limb) while all other muscles were collected bilaterally (i.e., contralateral and ipsilateral sides). EMG signals were bandpass filtered between 16 and 500 Hz and amplified (gain 1000). Surface areas were prepped for electrode placement by shaving, lightly abrading and cleaning with alcohol swipes then two disposable Ag/AgCl surface electrodes rectangular size 30 × 20 mm (Ambu® Blue Sensor N) were placed over the muscle belly 20 mm apart. Electrode placements for the MF, GM and BF were as per the European Recommendations for Surface Electromyography (Hermens et al., 2000) while the EO as per (McGill, Juker, & Kropf, 1996) and IO as per (Ng, Richardson, Kippers, & Parnianpour, 1998). Ground reaction forces and moments were measured with a force platform (AMTI LG6-3-1, AMTI, USA) collecting at 1000 Hz with an amplifier gain of 4000.

2.3. Procedure

The participants were asked to stand quietly on the force platform with feet positioned hip width apart. Upon hearing a distinctive auditory signal, they were to flex their hip to 90 ° as quickly as possible. The single leg lift task test to auditory signal was repeated 20 times for each leg. To minimize participant anticipation of the signal there was an inconsistent time interval between auditory signals. Both the dominant and the non-dominant limbs were tested in a random order. Limb dominance was examined via interview and functional task considering the preferred limb for kicking a ball and for balance recovery (Peters, 1988; Schneiders et al., 2010). Since the non-dominant lower limb appears to be specialized for balance control (Peters, 1988) and participants performed the task on both sides, we decided to include limb dominance in the statistical analysis.

2.4. Data processing

Ten trials per side (per participant) were randomly selected for the final analysis. All data were processed and analyzed using a purpose written Matlab® code (Version 7 R2011a, Mathworks, Natick, MA). Muscle onsets were identified by computer algorithm where activation was determined as the point at which the muscle activity first rose above baseline by 2SD and remained at this level for at least 50 ms (Hodges & Bui, 1996). Computer detected muscle onsets were visually verified. To determine muscle latencies with respect to the movements of interest, onset times were aligned to the initiation of weight shift (T_0) (Fig. 1). Trials were ignored if muscle onset activity occurred earlier than 30 ms after the auditory cue as the speed of muscle latency cannot be representative of a reflex related to the cue (Norman & Komi, 1979).

Kinematic data were tracked and processed using Vicon Nexus 1.8 (Vicon© Motion Systems Ltd, Oxford, UK) and exported as c3d files to Matlab® where it was filtered (using a recursive, low pass, fourth order Butterworth filter with a 10 Hz cut-off), interpolated to 1000 Hz and kinematics rendered. Leg lift onset (T_1) was defined as the initiation of movement of the swing limb in the vertical direction identified by computer algorithm and visually verified, from the interpolated kinematic data, as when the calcaneal marker trajectories on the lifted leg moved 2SD above baseline for more than 20 ms (Fig. 1). Timing of T_1 was normalized to T_0 such that the T_1 timing is representative of the APA duration (Yiou & Do, 2010). When the dominant limb was the moving limb it is referred to as "dominant limb condition", and when the non-dominant limb was the moving limb it is referred to as the "non-dominant limb condition". The APA amplitude was defined as the maximal medial-lateral center of pressure displacement (CoP_{ML}) occurring during the APA period (between T_0 and T_1) (Yiou & Do, 2010). CoP_{ML} displacement was computed as the ratio between the anterior-posterior axis moment and vertical ground reaction force. T_0 was defined as the initiation of weight shift toward the lifted leg and was identified by computer algorithm from the CoP_{ML} waveform as the instant where the magnitude of displacement deviated more than 2SDs from the mean baseline for more than 50 ms (Fig. 1). The CoP waveforms were baseline corrected and stance width standardized to hip width, no other normalization procedures were performed on the CoP data.

2.5. Primary outcome measures

Four primary outcome measures were considered: (i) weight shift onset (T_0), relative to the auditory signal and expressed in ms; (ii) APA duration taken as T_1 relative to T_0 and expressed in ms; (iii) activation onset for each muscle, relative to T_0 and expressed in ms; and (iv) medial-lateral displacement of center of pressure between T_0 and T_1 (CoP_{ML}), expressed in mm.

2.6. Data analysis

All statistical analysis of the data was undertaken with Statistica Version 8 software (Statsoft, Tulsa, OK). General linear model with an alpha of 0.05 was used to calculate three repeated measures ANOVAs: limb dominance condition (dominant and non-dominant) was considered as within-subject factor, sex as between-subject factor, and (i) T_0; (ii) APA duration; (iii) CoP_{ML} as

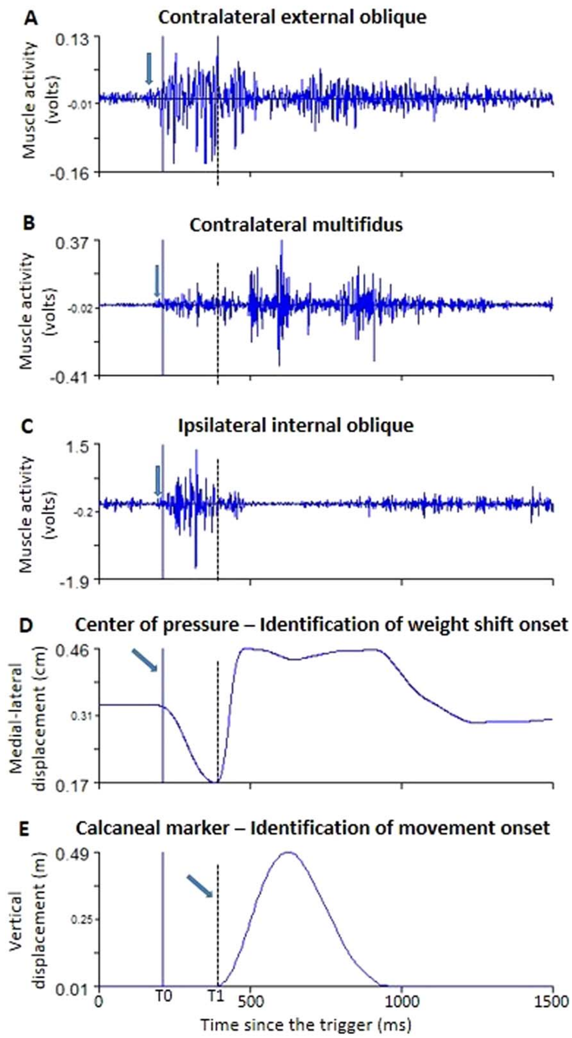

Fig. 1. Example trial from one representative participant showing (A) Contralateral external oblique activity, (B) Contralateral multifidus activity, (C) Ipsilateral transverse abdominis/internal oblique activity, (D) Medial-lateral center of pressure trajectory and identification of the initiation of weight shift – T_0, and (E) Vertical trajectory of the calcaneal marker and identification of leg lift onset – T_1. Arrows denote event detection; vertical lines denote T_0; and vertical dashed lines denote T_1.

dependent variables. In addition, one repeated measures MANOVA with limb dominance condition as within-subject factor, sex as between-subject factor, and activation onsets (ipsilateral EO, contralateral EO, ipsilateral IO, contralateral IO, ipsilateral MF, contralateral MF, BF and GM) as dependent variables was also calculated. Where significant interactions were found, the Fisher's least significant difference was calculated. The partial eta-squared (η^2) was used to measure effect size, considering η^2 lower than 0.061 as small, between 0.061 and 0.14 as medium, and above 0.14 as large effect sizes (Stevens, 2009).

3. Results

No differences in age ($p = .212$) and body mass index ($p = .643$) were observed between sexes (Table 1). Greater values of height ($p < .001$) and body mass ($p = .001$) were found for men compared to women. All participants were right-handed.

No statistically significant interactions between limb dominance and sex on T_0 ($F(1, 498) = 2.324$, $p = .128$, $\eta^2 = 0.004$) were observed (Fig. 2A). Statistically significant main effect of sex on T_0 ($F(1, 498) = 3.890$, $p = .049$, $\eta^2 = 0.007$) was observed. Men showed later T_0 compared to women (Table 2). No main effect of limb dominance on T_0 ($F(1, 498) = 3.21$, $p = .07$, $\eta^2 = 0.006$) was observed.

Statistically significant interactions between limb dominance and sex on APA duration ($F(1, 498) = 4.935$, $p = .026$, $\eta^2 = 0.010$) were observed (Fig. 2B). For men, similar APA duration was observed between lower limbs. Women showed later APA duration in the dominant limb condition compared to the non-dominant limb condition (Table 2) and similar values between sexes were observed in the non-dominant limb condition (Table 2).

Statistically significant interactions between limb dominance and sex on the CoP_{ML} ($F(1, 473) = 50.572$, $p < .001$, $\eta^2 = 0.097$)

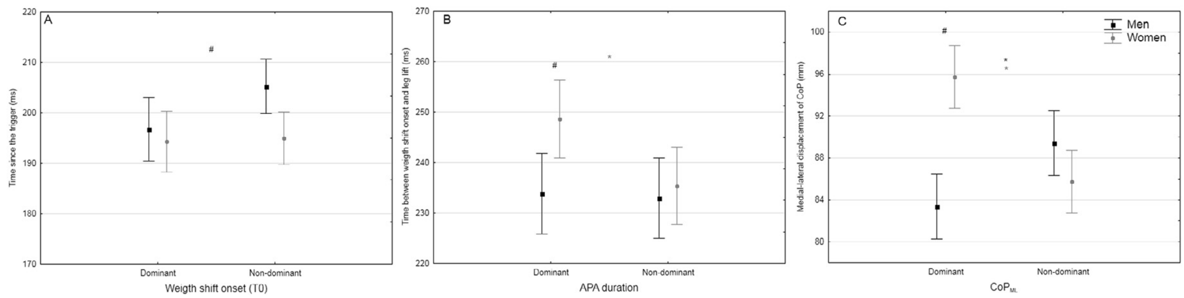

Fig. 2. Weight shift onset (T_0, A); APA duration (B) and APA amplitude (CoP_{ML}, C) (Mean and 95% confidence interval). #Statistically significant main effect of Sex ($p < .01$). *Statistically significant interaction between Sex and Limb Dominance ($p < .01$).

Table 2
Mean differences and respective 95% confidence intervals for weight shift onset (T_0), APA duration and medial-lateral displacement of center of pressure (CoP_{ML}).

Parameter	Main effect or Interaction	Mean diff.	95% Confidence limit		p
T_0 (ms)†	Men vs Women	6.35	0.02	12.70	.490
	Dominant vs Non-dominant	−4.45	9.51	0.60	.083
APA duration (ms)‡	Dominant limb: Men vs Women	−14.86	−25.94	−3.78	.008*
	Non-dominant limb: Men vs Women	−2.45	−13.53	8.62	.660
	Men: Dominant vs Non-dominant	0.88	−7.02	8.80	.825
	Women: Dominant vs Non-dominant	13.30	5.69	20.91	< .001*
CoPML (mm)‡	Dominant limb: Men vs Women	12.35	−16.63	−8.97	< .001*
	Non-dominant limb: Men vs Women	3.68	0.09	−0.60	.09
	Men: Dominant vs Non-dominant	−6.05	−9.23	−2.86	< .001*
	Women: Dominant vs Non-dominant	9.98	6.90	13.06	< .001*

† Main effects of sex and limb dominance.
‡ Interactions between sex and limb dominance.
* Statistically significant difference with $p < .05$.

were observed (Fig. 2C). During the dominant limb condition, women showed larger CoP_{ML} compared to men ($p < .001$), and no differences between sexes were found during the non-dominant limb condition ($p = .09$). When lower limbs were compared, female showed larger CoP_{ML} in the dominant limb condition ($p < .001$), whereas men showed the opposite, larger values ($p < .001$) in the non-dominant limb condition (Table 2).

Statistically significant interactions between limb dominance and sex were also observed on the activation onsets ($F(7, 3486) = 10.039$, $p < .001$, $\eta^2 = 0.02$ – Fig. 3). Women compared to men showed later onset in four out of the eight muscles in the dominant limb condition, and in six muscles in the non-dominant limb condition (Table 3). When lower limbs were compared, women showed later activation onset in the ipsilateral EO and BF and earlier onset in the contralateral IO and GM during the dominant limb condition compared to the non-dominant limb condition (Table 3). Men showed earlier onsets for the ipsilateral MF, GM and BF during the non-dominant limb condition, and for the ipsilateral EO in the dominant limb condition (Fig. 3).

4. Discussion

The purpose of this study was to examine the effect of sex on the timing of anticipatory weight shift (T_0), APA duration ($T_1 - T_0$), CoP_{ML} amplitude during APA period and muscle onsets during self-initiated perturbation in rapid single leg lift. Our hypothesis that the onset of muscle activity would be delayed and APA duration would be longer in women relative to men was partially supported, although the anticipated sex differences in APA duration and the CoP_{ML} amplitude were only expressed when the single leg lift was performed with the dominant limb. Interactions between sex and limb dominance were also found for activation onset latencies, although the importance of these differences is not clear since the effect sizes were generally small. The relationship between sex and limb dominance for measures of feed-forward control was an unexpected finding.

The interaction between sex and limb dominance observed in this study may be related to the different roles in movement control played by the dominant and non-dominant lower limbs. There is evidence to suggest that the non-dominant upper limb is specialized for impedance-based positional control and stabilizing tasks (Bagesteiro & Sainburg, 2002). Impedance describes frequency-dependent generalizations of resistance. In limb mechanics, it describes the complex relationship between deformation kinematics and the resulting torques as a function of the limbs mass, stiffness and dampening (Hogan, 1985a). The dominant limb is specialized for more complex trajectory or coordination tasks (Bagesteiro & Sainburg, 2002). A similar asymmetry of function appears to exist in the lower limb, with greater ankle stiffness in the non-dominant leg when weight-bearing (compared to the weight-bearing dominant leg) and greater lateral force generation when the dominant leg is weight-bearing during gait initiation (Dessery, Barbier, Gillet, & Corbeil, 2011). Since an increase in ankle stiffness would facilitate the translation of propulsive force into COP change and movement, it is possible that the asymmetries in APA duration and CoP_{ML} amplitude in our study were generated due to greater ankle stiffness in the

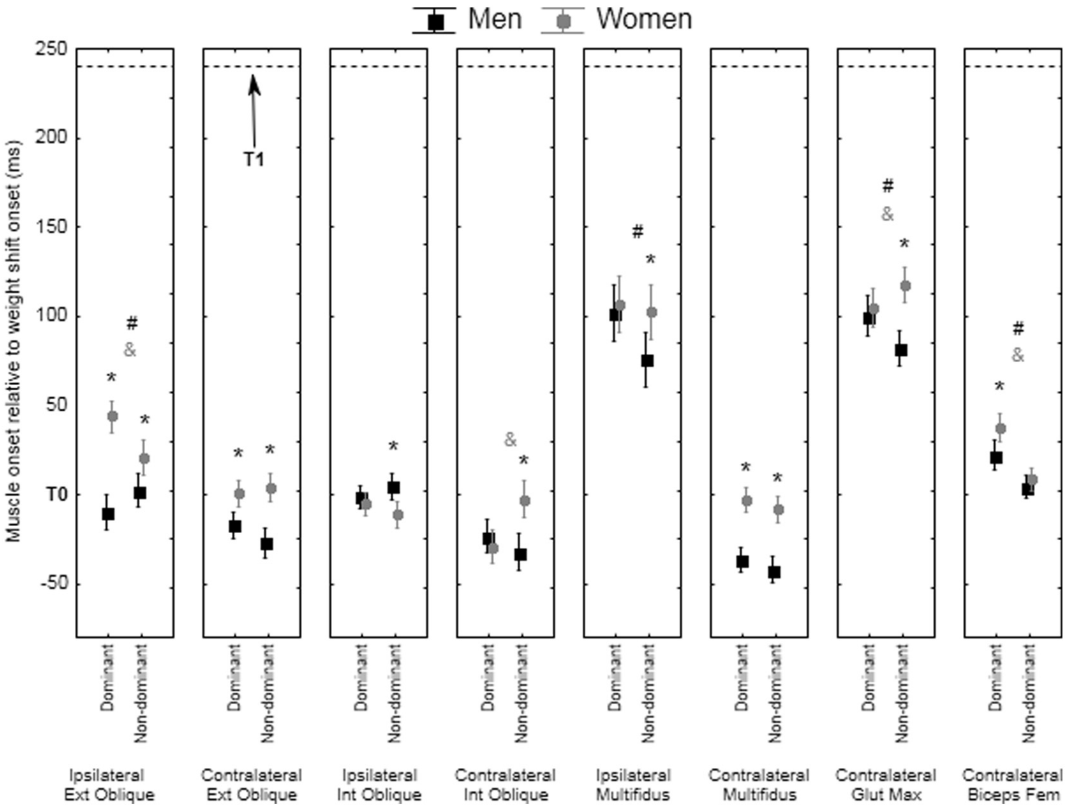

Fig. 3. Activation onsets (Mean and 95% confidence interval) related to APA. Superior dashed line indicates leg lift onset (T_1). Y-axis positive values denote muscle onsets that occur after weight shift onset (T_0) and negative values denote muscle activation prior to T_0. *Statistically significant difference between sexes ($p < .05$). #Statistically significant difference between male participants' lower limbs ($p < .05$). &Statistically significant difference between female participants' lower limbs ($p < .05$).

non-dominant stabilizing leg. Although this would be consistent with the data obtained during gait initiation, we cannot yet confirm this theory for single leg lifts, as we did not examine the activity in muscles crossing the ankle joint in this study.

The necessary creation of postural instability in preparation for movements such as the single leg lift may amplify the effects of bilateral control asymmetries and emphasize the importance of biarticular muscles for impedance regulation. The self-initiated single hip flexion task creates a transitory base of support, momentarily destabilizing the stance limb during the posterior medial shift of the center of pressure towards the swing limb. This, coupled with an increased lateral thrust provided by the non-dominant swing limb may explain the difference in BF muscle activity found between the dominant and non-dominant leg lifts. Earlier BF activity may be necessary to stabilize the hip and knee when preparing to balance on the non-specialized dominant limb. If increased swing limb thrust causes greater rotational velocity about the stabilizing hip, then it is plausible that earlier APA muscle response in the BF would be seen. Our findings show (in both sexes) a significantly earlier BF onset in the stabilizing hip when moving the non-dominant limb, indicating an earlier APA response in the hip stabilizing muscle, which supports this postulation (Fig. 3). Various authors have hypothesized bi-articular muscles are essential for regulating impedance and stability in multi-joint destabilizing tasks (Franklin, Osu, Burdet, Kawato, & Milner, 2003; Hogan, 1985b; McIntyre, Mussa-Ivaldi, & Bizzi, 1996). Walker and Perreault (2015) have also found greater feed-forward muscle activity in the upper limb muscles of the dominant limb during destabilizing tasks where the dominant limb was acting as a stabilizer and the authors noted a larger reflex response in the bi-articular muscles. It has been hypothesized limb dominance may reflect between-limb differences in feed-forward control, specifically task dynamics and modulation of limb impedance (Yadav & Sainburg, 2014). The results of our study support the postulation of bilateral differences in feed-forward control of lower limb stability during rapid hip flexion, and the idea that biarticular muscles such as the BF are particularly important for anticipatory impedance control in the non-dominant limb.

Based on the higher prevalence of pain conditions associated with low spinal stability in women, we hypothesized that women would display delayed anticipatory muscle actions before rapid postural transitions. This hypothesis was partially supported, since females experienced more significant muscle onset delays compared to males. In comparison with males, the 95% confidence limits indicated delays of muscle activation in females ranging between 4.9–31.7 ms (contralateral EO, dominant limb) to 41.1–67.8 ms (ipsilateral EO, non-dominant limb). It is tempting to suggest that activation delays for the IO, EO and MF in women compared to males indicate a mechanism for spinal instability due to a delay in stabilizing the lumbar spine ahead of load transfer in this high-speed movement task. We think that this conclusion would be premature however, because none of the muscles could be considered delayed with respect to the focal movement and there were significant sex-limb dominance interactions that did not follow a clear

Table 3
Mean difference and respective 95% confidence limits of the interactions between sex and limb dominance in activation onsets.

	Muscles	Mean diff. (ms)	95% Confidence limit		p
Dominant limb: Men vs Women	Ipsilateral Ext Oblique	−54.4	−67.8	−41.1	< .001*
	Contralateral Ext Oblique	−17.7	−31.0	−4.3	.010*
	Ipsilateral Int Oblique	4.2	−9.2	17.5	.541
	Contralateral Int Oblique	5.9	−7.5	19.3	.385
	Ipsilateral Multifidus	−5.1	−18.5	8.3	.456
	Contralateral Multifidus	−33.2	−46.6	−19.8	< .001*
	Contralateral Glut Max	−4.7	−18.1	8.7	.491
	Contralateral Biceps Fem	−15.5	−28.9	−2.1	.023*
Non-dominant limb: Men vs Women	Ipsilateral Ext Oblique	−18.3	−31.7	−4.9	.007*
	Contralateral Ext Oblique	−31.0	−44.3	−17.6	< .001*
	Ipsilateral Int Oblique	15.5	2.2	28.9	.023*
	Contralateral Int Oblique	−29.6	−43.0	−16.2	< .001*
	Ipsilateral Multifidus	−26.7	−4.0	−13.3	< .001*
	Contralateral Multifidus	−33.7	−47.1	−2.4	< .001*
	Contralateral Glut Max	−35.7	−49.1	−22.3	< .001*
	Contralateral Biceps Fem	−8.0	−18.7	2.7	.144
Men: Dominant vs Non-dominant	Ipsilateral Ext Oblique	−12.1	−22.8	−1.4	.027*
	Contralateral Ext Oblique	9.9	−0.8	20.6	.070
	Ipsilateral Int Oblique	−5.6	−16.3	5.1	.304
	Contralateral Int Oblique	9.1	−1.7	19.8	.098
	Ipsilateral Multifidus	26.3	15.6	37.0	< .001*
	Contralateral Multifidus	5.7	−5.1	16.4	.301
	Contralateral Glut Max	18.3	7.6	29.1	.001*
	Contralateral Biceps Fem	17.9	7.1	28.6	.001*
Women: Dominant vs Non-dominant	Ipsilateral Ext Oblique	24.1	13.4	34.8	< .001*
	Contralateral Ext Oblique	−3.4	−14.1	7.3	.535
	Ipsilateral Int Oblique	5.8	−5.0	16.5	.293
	Contralateral Int Oblique	−26.5	−37.2	−15.8	< .001*
	Ipsilateral Multifidus	4.7	−6.0	15.4	.387
	Contralateral Multifidus	5.1	−5.6	15.8	.349
	Contralateral Glut Max	−12.7	−23.4	−2.0	.021*
	Contralateral Biceps Fem	29.1	18.4	39.8	< .001*

* Statistically significant difference with $p < .05$.

pattern. For instance, the contralateral IO was activated earlier in women but the ipsilateral EO was activated later when the dominant limb was the moving limb. Whether these activation delays are related to spinal stabilization is an interesting question however, with potentially important ramifications for the prevention and management of low back pain.

If the creation of postural instability during transitions between static and dynamic modes of postural control necessitates feed-forward muscle activation, it follows that the amount of instability should dictate the timing and magnitude of that activity. Transitions carried out under conditions of relatively low stability would be expected to require early and large anticipatory actions to reduce the impact of the postural perturbation. In this context, the fact that women in our study demonstrated delayed activation in many muscles responsible for trunk and pelvic control may reflect a movement being carried out under conditions of relatively high stability. This idea is supported by previous research showing that females are significantly more stable during single leg balance testing than their male counterparts (Cuğ, Özdemİr, & Ak, 2014; Rozzi, Lephart, Gear, & Fu, 1999). APA responses are scaled to the predictive consequences of the focal movement, thus, greater threats to stability require earlier muscle onsets (Bouisset, Richardson, & Zattara, 2000). If female biomechanics or muscular control, provides more stability during single leg balancing we would expect their feed-forward muscle response to be more delayed compared to males for the same task, as was demonstrated in this study. Clearly further work is required to elucidate the mechanisms behind these responses.

This study has some limitations. First, the surface EMG method on the IO muscle has been shown to have considerable crosstalk with the as transverse abdominis, which limits our ability to differentiate specific muscle fiber action from the deep muscle tissue. While every effort was made to match the participants (age and body mass index) to maintain similar relative loading, males are generally heavier and taller than females and it is possible that physiological or anatomical differences may have an effect on muscle onset timing. It is unlikely that any such effect is due to differences in limb inertia however, since a large proportion of the mass difference between males and females is due to muscle mass, meaning that increases in inertia are compensated for by concomitant increases in the capacity for muscular force generation. It has been suggested that increased inertial loading may increase background EMG activity in proximal muscles (Aruin & Latash, 1995), however, we did not find any difference in the background activity between sexes. Finally, we used the Fisher's least significant difference when significant interactions were found. Thus we did not apply corrections for multiple comparisons. This approach was adopted because of the exploratory nature of the current study. We aimed to identify parameters that could be subject to more rigorous future examination.

Since the focus of the current study was on anticipatory control, no distinction was made between reflex and voluntary forms of feedback control. It has been suggested that feedback-driven control of spinal stability may be regulated differently in men and women, which may affect susceptibility to low back pain (Granata, Orishimo, & Sanford, 2001). Previous work has found that reflexive activation of the erector spinae along with the IO, EO and MF significantly contribute to the rotational stiffness at L_{4-5} and that such reflexive muscle force may be important to joint integrity during voluntary and involuntary movement (Cort, Dickey, & Potvin, 2013). Females are also known to have shorter stretch reflex latencies in the erector spinae muscles (48 ms vs 60 ms) (Miller, Slota, Agnew, & Madigan, 2010) which allows earlier involuntary control of the lumbar spine. Early reflex action may form an important part of the spinal stabilization response for women, and may suggest a greater reliance on reflex circuit activation to compensate for delayed or inaccurate anticipatory commands. The fact that males have been shown to have faster reaction times for voluntary movement in response to both visual and auditory cues compared to females (Jain, Bansal, Kumar, & Singh, 2015), lends support to the idea that women (on average) may need to rely more heavily on involuntary feedback control mechanisms due to delayed voluntary reactions. Experiments that specifically distinguish between anticipatory, reflex and voluntary actions during self-initiated postural disturbances would help to identify the relative importance of each form of control to spinal stability and the development of low back pain.

5. Conclusion

In conclusion, the findings of the current study indicate that males and females differ in their anticipatory postural control strategy for single leg lift, and that limb dominance play a role influencing APA differently across sexes. Women showed increased APA duration and magnitude (CoP_{ML}) in their dominant limbs compared to men. Such differences between sexes did not occur in the non-dominant limb. Considering muscle onsets, women recruited proximal muscles such as the EO, IO and MF later than their male counterparts. Overall women appear to have a stronger effect of limb dominance on their anticipatory postural control strategy which requires further investigation. Further, the findings show that anticipatory activation of the BF muscle is dependent upon limb dominance in both sexes, supporting and extending theories of limb specialization. Additional investigation of the putative anatomical and physiological differences between men and women that may underlie sex-based differences in the temporal structure of APAs is needed to fully understand their significance.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2017.10.003.

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