Fatigue task-dependent effect on spatial distribution of lumbar muscles activity

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Introduction

Lumbar muscle fatigue can occur when performing prolonged or repeated common daily tasks, such as standing (Allison and Henry, 2001), bending forward (Bonato et al., 2003) or even while sitting without back support (Jung et al., 2021). Many studies have reported lower lumbar muscle endurance in patients with chronic low back pain (Demoulin et al., 2007, Moffroid, 1997, Roy et al., 1989, Süüden et al., 2008). The new theory for motor adaptation to pain proposes that a redistribution of activity occurs between and within trunk muscles in the presence of pain (Hodges and Tucker, 2011), which supports recent evidence showing an alteration in the lumbar muscle recruitment strategy under the influence of muscle fatigue in patients with low back pain (Arvanitidis et al., 2021, Arvanitidis et al., 2022, Falla et al., 2014, Sanderson et al., 2019).

With recent advances in electromyography (EMG) technologies such as high-density EMG (HD-EMG), many studies have reported changes in spatial distribution of lumbar muscle activation during sustained contractions, suggesting recruitment of different lumbar regions under the influence of muscle fatigue (Abboud et al., 2015, Sanderson,Martinez-Valdes, 2019, Tucker et al., 2009). The ability to recruit different regions in the superficial lumbar muscles could be explained by its anatomical configuration with multiple origins and insertions and different muscle fiber orientations (Macintosh and Bogduk, 1987). Moreover, it has been recently shown, using indwelling EMG, that healthy individuals are able to distinctly activate the upper and lower regions of the lumbar muscles during various functional tasks (Abboud et al., 2020). From a clinical standpoint, the spatial shift enabling the recruitment of muscle activity in different lumbar regions could have important significance such as redistributing spinal loads on the spine and delaying the apparition of muscle fatigue (Falla and Gallina, 2020).

Muscle fatigue-related motor adaptations can also depend on the task (Bigland-Ritchie et al., 1995). Performing motor tasks in different trunk postures leads to a variation in lumbar muscle fiber orientations (Harriss and Brown, 2015) which could allow new lumbar muscle recruitment strategies (Abboud et al., 2023). It could therefore be argued that lumbar muscle recruitment strategies are task-dependent. A few studies have compared different tasks inducing lumbar muscle fatigue

(Champagne et al., 2008, da Silva et al., 2005, Russ et al., 2018) and results from these studies mainly showed a task-dependent effect on endurance time and EMG fatigue indices, such as median frequency. Task-dependent muscle activity spatial distribution was previously investigated in the rectus femoris by (Watanabe et al., 2012) and results showed a clear task-dependent effect on regional activation of this muscle. How lumbar muscle spatial recruitment strategy is modulated by the task under the influence of muscle fatigue remains, however, to be determined. The aim of this study is to identify whether lumbar erector spinae muscle recruitment is modulated by the fatigue task characteristics. We hypothesized that regional activation of the superficial lumbar muscles is task-dependent and that such task-dependency will be reflected in the spatial distribution of muscle activity.

Methods

Participants

Twenty adult participants (12 men and 8 women) were recruited for this study. The lowest sample size to reach a power of 80% and detect significant time effect of moderate effect size using an α error of 5% was n=19 for a repeated measure ANOVA (calculated with G*Power 3.1.9 software). Participants were excluded if they experienced one or more low back pain episodes in the past year. Moreover, any pain that prevented the task from being performed was considered an exclusion criterion. An experienced clinician (EMB) screened and established eligibility to participate in the study for each participant. Participants mean for age, weight, height, and BMI were respectively: 28.2 ± 6.1 years, 71.5 ± 12.5 kg, 170.8 ± 8.2 cm and 24.4 ± 2.9 kg/m2. Participants were recruited within the university community and via social media. The project received approval from the Research Ethics Board for human research of the "Université du Québec à Trois-Rivières" (CER-20-264-07.01). All participants provided written informed consent, acknowledging their right to withdraw from the experiment without consequences. All experimental procedures conformed to the standards set by the latest revision of the Declaration of Helsinki.

Study Design

Recruitment and data collection were conducted in Québec, Canada from January 2022 to January 2023. The experimental protocol was conducted over one session lasting approximately 2 hours. During this session, lumbar muscle recruitment strategies were assessed during two distinct lumbar muscle fatigue tasks: the modified Sorensen test and the inverted modified Sorensen test. These two tasks were separated by a 30-min period of rest and were randomized between participants.

Experimental Protocol

The modified Sorensen test consists of an endurance test performed in the prone position with a 40-degree flexion between the trunk and the lower limbs (Figure 1). The iliac crests are aligned with the edge of the chair cushion and straps were added at the hip and the ankles. In this position, the trunk of participants is unsupported in a horizontal position relative to the ground. The inverted modified Sorensen test consists of an endurance test in a prone position with the same 40-degree flexion between the trunk and the lower limbs (Figure 1) (Dedering et al., 1999). In this position, the lower limbs are unsupported in a horizontal position relative to the ground with participants' arms at their side. Straps at the hip and the thoracic region are added. For both endurance tests, participants are installed on a surgical tilting table. The angle between the trunk and the hip was verified using an inclinometer (Precision: ±0.1°; Johnson, digital angle locator, model 40–6067, Mequon, WI, USA).

Before each endurance task, participants were instructed to perform three maximal voluntary isometric extension contractions (MVC). In the modified Sorensen test condition, these contractions were performed against a leather belt installed over their shoulders. In the inverted modified Sorensen test, the leather belt was installed over the calves (midway between the popliteal fossa and distal insertion of Achilles tendon). The belt was linked to a load cell (Model LSB350; Futek Advanced Sensor Technology Inc, Irvine, CA, USA) through a cable that was fixed to the ground.

Participants were instructed to perform each MVC for 5 s. A one-minute rest period was offered between each MVC. Thirty percent of the highest MVC value for each test was used for the endurance tasks. Participants had to maintain this target until exhaustion. A computer screen was used to provide constant feedback on the force level developed by the participant (target of 30 % of MVC). Two lines indicating, respectively, 25 and 35 % of MVC were used to define the MVC range permitted during the endurance tasks. As soon as the participants were out of the target range, the assessor asked the participants to correct the force. The test ended when a participant was no longer able to reach the target for more than three seconds (Demoulin et al., 2016).

Data Collection

Superficial lumbar extensor muscle activity was recorded bilaterally with two grids of 64 electrodes arranged in 8 columns and 8 rows (10 mm inter-electrode distance; 8 cm by 8 cm; material Cu + chemical gilding; semi disposable adhesive matrix; model ELSCH064, OTBioelettronica, Torino, Italy) which cover approximately L1 to L4-L5 region. The electrodes remained in place between the two fatigue tests. All edges of the grids were taped to avoid any movements of the electrodes on the skin. Prior to the application of electrodes, the recording sites were cleaned with fine-grade sandpaper (Red Dot Trace Prep; 3 M, St. Paul, MN), and shaved. Both grids were placed along the approximate fiber orientation of the superficial lumbar muscles. The medial edge of the grid was at ~1 cm from the lumbar spinous process and the center was located at L3 level identified by palpation. This median location was chosen because the size of the grid was the same for all participants while participants' height was different. The reference electrode was placed over the left posterior superior iliac spine. During the data collection, vertical differential EMG signals were sampled at 2048 Hz, amplified by a factor of 2000 or 5000 and converted to digital (12-bit A/D converter; 128-channel EMG-USB; OTBioelettronica; –3 dB, bandwidths 10–500 Hz).

Data Analysis

The last row of each grid was removed because differential signals were collected, providing two final grids of 56 electrodes; 8 columns and 7 rows. First, a band-pass filtered was applied to all EMG signals (frequency bandwidth 20-400 Hz; 4th order Butterworth filter). Second, notch filters were also applied to all signals to eliminate the 60 Hz power line interference and its harmonics (2nd order Butterworth filter). Third, visual inspection of all EMG signals was performed by the same assessor to identify electrodes with low signal-to-noise ratio. These electrode signals were reconstructed by the interpolation of the neighbouring electrodes. If these electrode artifacts were excessive (≥6 electrodes (10%)), the entire recording was removed from the data analysis (Gallina et al., 2022).

Each electrode-filtered signal was then divided in windows of one second without overlap for which an individual root mean square (RMS) value was computed. Spatial distribution of the superficial lumbar extensor muscles was computed using the x-axis (medio-lateral) and y-axis (cranio-caudal) coordinates of the centroid during both endurance tasks. The centroid was defined as the average weighted position of the electrodes exhibiting EMG amplitude (RMS) values higher than 70% of the maximum of all electrodes (Gallina,Disselhorst-Klug, 2022, Vieira et al., 2010). The centroid was computed on the interpolated maps when electrode signals were reconstructed. The position of the origin point (0,0) for the centroid was on the left bottom corner of both grids. The grid on the right side was flipped along the x-axis, so that higher x-coordinates indicated a more medial location of the centroid on both sides similarly to the left side. For each participant, each endurance tasks were divided into six equal and consecutive time periods (phases). The x- and y-axis coordinates of the centroid were computed in each phase. The mean normalized RMS value trial was also computed in each phase to assess the contribution of the lumbar erector spinae in each task. The RMS from both endurance tasks was normalized with EMG RMS from the highest MVC trial. To confirm the presence of lumbar muscle fatigue in both tasks, a median frequency value (mean of all electrodes of each grid) was computed in six equal and consecutive windows for each participant (Cifrek et al., 2009). The median frequency algorithm estimates the median normalized frequency of the power spectrum of a time-domain signal. Then, the slope of the median frequency was calculated. The endurance time of each task was also recorded. HD-EMG data from the left and right sides were analyzed separately. HD-EMG signals were analyzed using a custom script on Matlab (2022b version, Mathworks, Natick, MA, USA).

Statistical Analysis

The normality of the data was assessed with Kolmogorov-Smirnov test and by visual inspection. Within-subject two-way repeated-measure ANOVAs were conducted to assess the effect of endurance tasks (modified Sorensen test and inverted modified Sorensen test), time (6 phases) and interaction (endurance task*time) on the x- and y-axis coordinates of the centroid as well as the normalized RMS. When significant differences were identified, a post-hoc test (Bonferroni) was performed to decompose the main effects using pairwise comparisons. Median frequency slopes, endurance times and MVCs were compared between endurance tasks using *t* tests for dependent samples. Effect size of significant difference was calculated using partial eta-squared (ηp^2; 0.01 = small effect; 0.06 = medium effect; 0.14 = large effect) (Cohen, 2013). All statistical analyses were performed with Statistica software version 13 (TIBCO Software Inc, Palo Alto, CA, USA) with an alpha level set at 0.05.

Results

All participants were able to complete both endurance task until exhaustion. Significantly longer endurance times were observed during the inverted modified Sorensen in comparison to the modified Sorensen test (Table 1). Significantly higher MVC was observed in the modified Sorensen position in comparison to the inverted modified Sorensen (Table 1). Median frequency slopes were negative for all participants in both tasks and sides and results showed no difference between endurance tasks (Table 1).

A significant increase of RMS value was observed over time on both the right [$F(5,95) = 9.35$, $p < 0.001$, $\eta p^2 = 0.33$] and left [$F(5,95) = 10.74$, $p < 0.001$, $\eta p^2 = 0.36$] sides. No significant effect of endurance task was observed for the RMS ($p = 0.61$ for the right side and $p = 0.21$ for the left side). The mean normalized RMS values on the right side was 37.3% (SD=1.9) for the modified Sorensen test compared to 36.1% (SD=2.7) for the inverted Sorensen test. On the left side, the RMS values were 39.6% (SD=2.6) for the modified Sorensen test compared to 36.0% (SD=2.6) for the inverted Sorensen test. No significant interaction effect (endurance task*time) was observed for the RMS ($p = 0.07$ for the right side and $p = 0.56$ for the left side).

The ANOVA revealed a significant effect of time for the x-axis coordinates of the centroid on both the right [$F(5,95) = 14.62$, $p < 0.001$, $\eta p^2 = 0.43$] and left [$F(5,95) = 21.58$, $p < 0.001$, $\eta p^2 = 0.53$] sides (Figure 2). A lateral shift of the centroid was observed across time (Figure 3). Post-hoc results showed a significantly more lateral location of the centroid in phase 6 compared to all previous phases (Bonferroni-test ps < 0.005) on the left side and compared to the first 4 phases on the right side (Bonferroni-test ps < 0.001). The same results were observed in phase 5 compared to the first 3 phases on both sides (Bonferroni- test ps < 0.05). Finally, a significantly more lateral location of the centroid was observed in phase 4 compared to phase 1 on the left side (Bonferroni-test $p = 0.04$). No significant effect of endurance task was observed for the x-axis coordinates of the centroid ($p = 0.94$ for the right side and $p = 0.11$ for the left side).

No significant effect of time was observed for the y-axis coordinates of the centroid ($p = 0.42$ for the right side and $p = 0.053$ for the left side). No significant effect of endurance task was observed for the y-axis coordinates of the centroid ($p = 0.61$ for the right side and $p = 0.07$ for the left side). Significant endurance task*time interactions were found for the y-axis coordinates on the right [$F(5,95) = 2.76$, $p = 0.02$, $\eta p^2 = 0.13$] and left [$F(5,95) = 5.63$, $p < 0.001$, $\eta p^2 = 0.22$] sides (Figures 2-3). Post-hoc results showed a significantly more caudal location of the centroid in the modified Sorensen test compared to the inverted modified Sorensen test in the first 3 phases on the left side (Bonferroni-test ps < 0.001). On the right side, post-hoc results showed a significantly more caudal location of the centroid in phase 1 of the modified Sorensen test compared to the inverted modified Sorensen test (Bonferroni- test p = 0.04).

Discussion

The aim of the current study was to investigate the effect of two different low back endurance tasks on superficial lumbar muscle recruitment strategies. Our hypothesis was partially confirmed as our results showed that, in response to low back muscle fatigue, the regional activation of superficial lumbar muscles in healthy individuals is task-dependent, only in a pre-fatigue stage and in the cranio-caudal axis.

In the present study, individuals were asked to perform two different lumbar endurance tasks, the modified Sorensen test and the inverted modified Sorensen test. The modified Sorensen test is commonly used as a valid alternative to the Sorensen test when assessing lumbar muscle endurance (Champagne,Descarreaux, 2008, Dedering,Németh, 1999, Demoulin et al., 2006). To avoid a carry-over effect of muscle fatigue in the second task, a rest period of 30 minutes was added between tasks and the order were randomized between individuals. A previous study reported that 10 to 15 minutes are sufficient for trunk extensor muscle to recover from muscle fatigue (Larivière et al., 2003). Despite a longer endurance time during the inverted Sorensen test, which could be explained by a higher MVC value obtained in the Sorensen position, median frequency slopes were negative in both endurance tasks and were not significantly different between these two tasks. A decrease in EMG power spectrum median frequency is considered one of the best indicators of muscle fatigue myoelectric manifestations (Goubault et al., 2022, Mannion and Dolan, 1994). In our study, median frequency slopes were not modulated by the tasks which suggest that individuals experienced a similar level of lumbar muscle fatigue in both tasks. Previous studies have described a task dependency effect on the lumbar muscle median frequency (Champagne,Descarreaux, 2008, da Silva,Arsenault, 2005). A possible explanation for the conflicting results is the differences in participants' positions chosen to perform lumbar endurance tasks. In the Champagne et al. (2008) study, lumbar muscle fatigue was assessed using the

Sorensen test (trunk parallel to the ground) and the modified Sorensen test, which are performed using different trunk angles. In the study published by da Silva et al. (2005), individuals performed three different lumbar endurance tests: in an upright position, in a semi crouched position and in the Sorensen test position. In the current study, individuals performed two endurance tasks using the same angle between trunk and lower limbs, while previous studies used lumbar fatigue protocols with different trunk angles and postures. The endurance tasks performed in the present study were chosen to avoid changes in lumbar muscles fiber orientations which can modify spatial distribution of lumbar muscles (Abboud,Ducas, 2023). The differences between these tasks were the lever arm of the resistance and the weight of the trunk in comparison to the lower limbs. Despite these differences, the current study showed no significant task difference in the EMG amplitude of the erector spinae muscles, which suggest a similar contribution of these muscles in each task. The contribution of the lower limb muscles, especially during the inverted Sorensen cannot be excluded and future studies should assess the contribution of these muscles to confirm their role in this task.

Using HD-EMG, our study showed a task dependency effect on the cranio-caudal coordinates of the centroid. More specifically, the EMG distribution was more cranial during the inverted modified Sorensen test compared to the modified Sorensen test in early stages of both tasks, especially on the left side. For the erector spinae on the right side, this task-dependent effect was only present in the first phase of the endurance tasks. The differences observed between sides warrant further investigation. During the modified Sorensen test, the resistance was placed at the thoracic region and at the hip during the inverted Sorensen test. From a biomechanical standpoint, it can be argued that a longer lever arm of the muscular force is prioritized to oppose the moment arm generated by the resistance. Therefore, during the inverted modified Sorensen test, recruiting the lumbar muscle cranial region would represent the highest mechanical advantage to perform this task and would consequently reduce the functional cost associated with the task. Interestingly, at the end of the tasks, the difference in spatial distribution between both endurance tasks disappeared. During the inverted modified Sorensen test, the centroid of muscle activity gradually shifts toward a caudal direction similar to the y-axis coordinates observed in the modified Sorensen test. These findings suggest that healthy individuals seek a new motor solution to preserve performance under the influence of muscle fatigue (Cè et al., 2020, Fuller et al., 2011) and this solution may not be task-dependent. The complexity of the trunk system offers a multitude of motor recruitment solutions to perform a task. Thus, it can be speculated that muscle fibers fatigability in more constrained conditions such as low back isometric contractions decrease the range of motor solutions leaving a unique alternative to preserve the performance of these tasks. Further research is needed to confirm this hypothesis in dynamic tasks where more degrees of freedom are available.

Our results also revealed that, in response to muscle fatigue, a clear lateral migration on the left and right sides of lumbar muscle activity was similar in both endurance tasks. As opposed to the cranio-caudal differences occurring during the inverted modified Sorensen test, the medio-lateral changes occurred mostly at the end of both endurance tasks. This spatial activation strategy suggests a higher contribution of the more lateral components of the erector spinae muscles, such as the longissimus, at the end of both endurance tasks. This finding could be explained by the erector spinae muscles role which are considered the main contributor to trunk extension given their fiber orientation (McGill et al., 1993). On the other hand, a more medial location of the centroid suggests a higher contribution of the superficial multifidus at the beginning of the tasks. According to our study results, we can hypothesize that the lumbar muscle components with the highest mechanical advantage are preferentially recruited under the influence of muscle fatigue regardless of the motor task. One could also argue that in order to preserve motor performance during an endurance task, muscle activity may migrate to a less fatigued region of the muscle. Future research should selectively record the contribution of each lumbar muscles and their region under the influence of muscle fatigue to better understand this motor strategy.

The migration of the centroid location has been increasingly used to better understand the neuromuscular adaptations to low back pain suggesting a redistribution activity within and/or between trunk muscles (Hodges and Tucker, 2011). Even small changes in muscle activity spatial distribution are clinically relevant as previous studies comparing healthy individuals to patients with low back pain found differences of centroid location between groups as small as the one reported in the current study (Arvanitidis,Bikinis, 2021, Falla,Gizzi, 2014, Sanderson,Martinez-Valdes, 2019). Future studies should investigate whether individuals with patients with chronic low back pain exhibit task-dependent muscle behaviour similar to alterations in regional activation of lumbar erector spinae muscles. Exploring this possibility may provide insights into the effectiveness of retraining individuals with chronic low back pain using exercises that target the lower portion of their lumbar erector spinae alongside HD-EMG biofeedback. Such investigations could shed light on the potential impact on symptom management.

The present study has some limitations that should be considered. EMG recordings were limited to the superficial lumbar muscles while the hip extensors also contribute to trunk extension, especially during the inverted Sorensen. To minimize the contribution of these muscles during these tasks, straps were used to stabilize the hip, as previously suggested (da Silva et al., 2009). A small sample size increases the risk of type II statistical error. However, most of the main and interaction effects were highly significant with large effect sizes indicating the high magnitude of the difference of the centroid migration between the two conditions. Result interpretations should be limited to isometric control tasks which may not be as representative as all real-life motor tasks. Participants were not asked to avoid any strenuous activity prior to participation, but we believe that it did not impact our results because participants were compared to themselves. Finally, the interpretation should also be limited to a healthy young adult population.

Conclusion

The current study revealed that the cranio-caudal regional activation of the superficial lumbar muscles in healthy individuals is task-dependent, only at a pre-fatigue stage. The spatial distribution in the caudal-cranial direction was influenced by the task, revealing a higher contribution of the region with the higher mechanical advantage. This task-dependent effect was not present in the medio-lateral spatial distribution of muscle activity. Under the influence of muscle fatigue, the difference in spatial distribution between both endurance tasks disappeared. Finally, the study also revealed a clear lateral migration of lumbar muscle activity at the end of both endurance tasks, suggesting that healthy individuals seek a common new motor solution to preserve motor performance under the influence of muscle fatigue.

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Table 1. Mean values (standard deviations (SD)) for median frequency (MDF) slope, endurance time (seconds) for both endurance tasks, and MVC (kg) in each position. *p based on t-tests for dependent samples.

	Modified Sorensen	Inverted modified Sorensen	p value*
MDF slope			
Right side	-3.32 (2.19)	-3.69 (2.10)	0.43
Left side	-3.31 (1.70)	-3.54 (1.57)	0.57
Endurance time (seconds)	137.4 (40.0)	227.1 (71.3)	0.001
MVC (kg)	62.9 (21.8)	39.4 (15.9)	0.001

Captions to illustrations

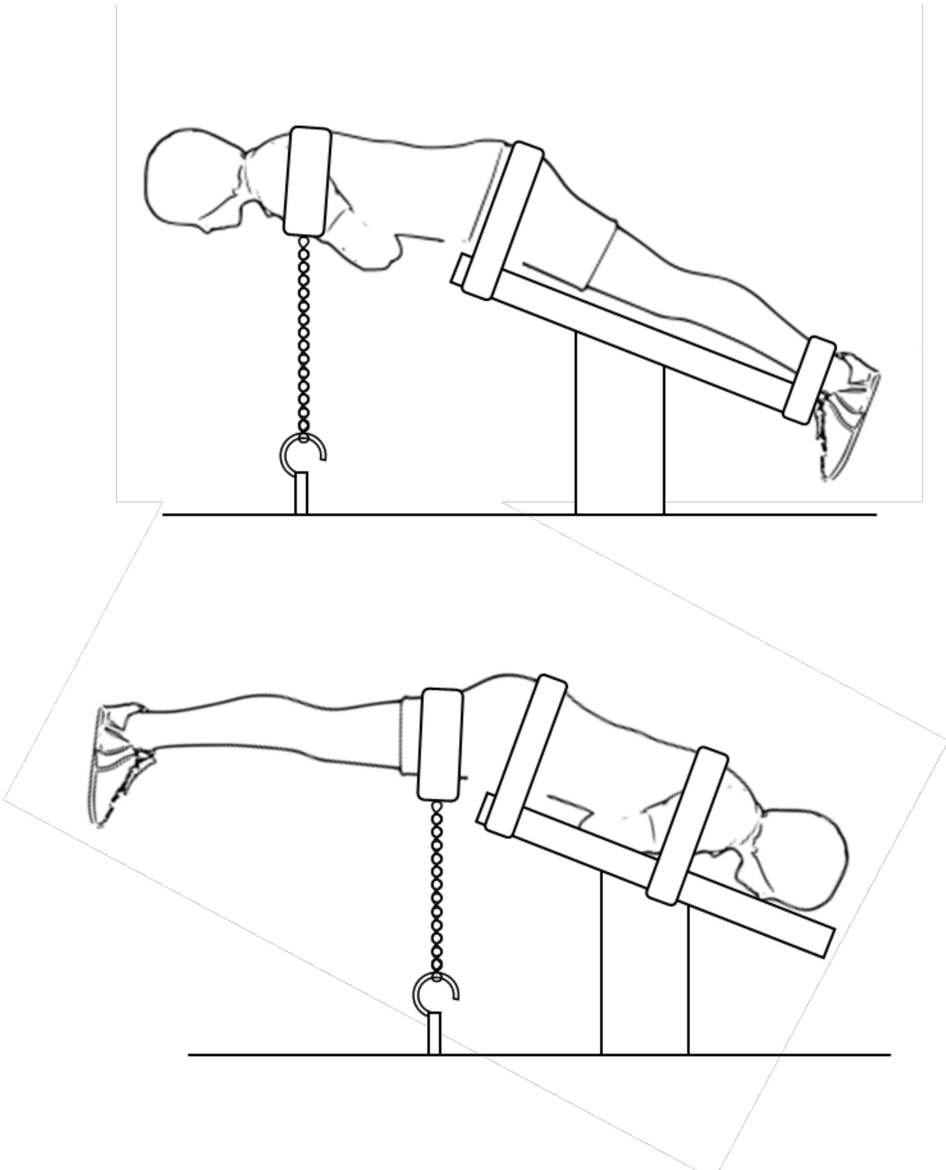

Figure 1. Illustration of the modified Sorensen test (A) and the inverted modified Sorensen test (B). On both tasks, the angle between the hip and trunk is the same.

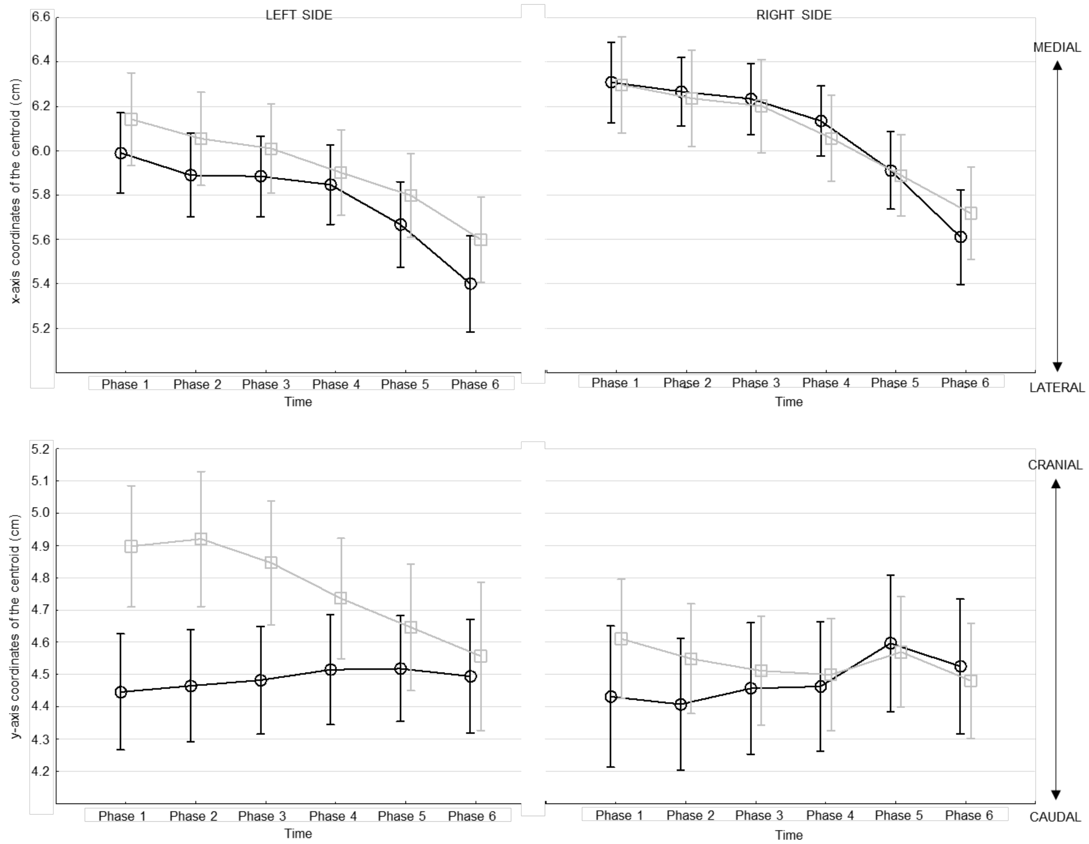

Figure 2. Medio-lateral (x-axis) and cranio-caudal (y-axis) coordinates of the centroid locations during the modified Sorensen (black lines) and the inverted modified Sorensen (grey lines). These coordinates represent the location of the centroid on each EMG grid. Circles and squares represent the means and vertical bars represent the standard errors.

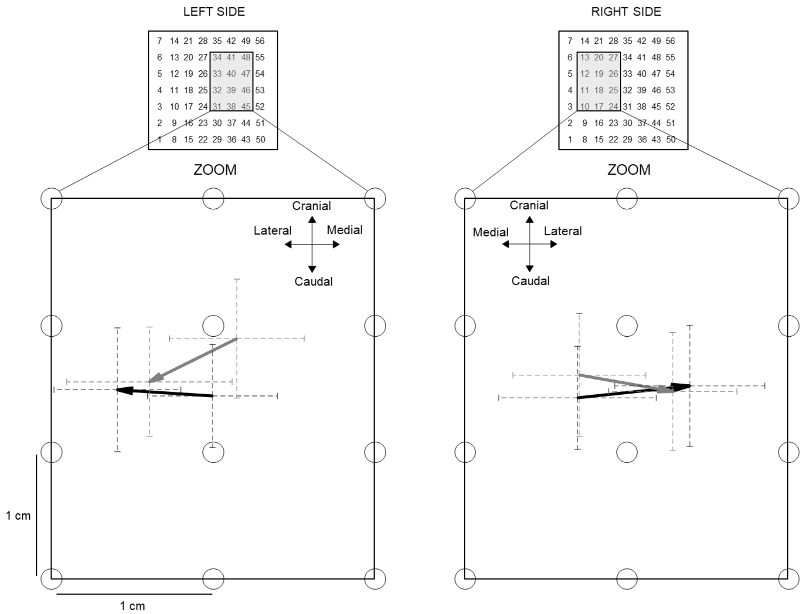

Figure 3. Illustration of the centroid migration during the modified Sorensen (black arrow) and the inverted modified Sorensen (grey arrow). The arrows represent the average direction of the centroid shift. Bars represent the standard deviations.