TITLE: DIFFERENCES IN LINEA ALBA STIFFNESS AND LINEA ALBA DISTORTION BETWEEN WOMEN WITH AND WITHOUT DIASTASIS RECTI ABDOMINIS: THE IMPACT OF MEASUREMENT SITE AND TASK.

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ABSTRACT

STUDY DESIGN: cross-sectional, observational cohort

BACKGROUND: The biomechanical implications of diastasis recti abdominis (DRA) are unknown.

OBJECTIVES: (1) To investigate the impact of DRA, measurement site and task on inter-rectus distance (IRD), linea alba (LA) stiffness and LA distortion measured at rest, and during head lift and semi-curl-up tasks. (2) To describe the relationships among IRD, LA stiffness and LA distortion.

METHODS: B-mode ultrasound imaging and shear-wave elastography were used on a sample of 20 women. IRD, LA stiffness and LA distortion were measured at three locations while women were at rest, and repeated head lift and semi-curl-up maneuvers. All outcomes were compared between groups (DRA/no DRA), sites and tasks. Linear regression models were used to evaluate the relationships among IRD, mean and peak LA stiffness and LA distortion.

RESULTS: Eleven women with and nine without DRA participated. Women with DRA demonstrated lower peak and mean LA stiffness and higher LA distortion compared to women without DRA. In women with DRA, IRD and LA distortion were not influenced by measurement site; IRD decreased, LA distortion increased and LA stiffness did not change during the head lift and semi-curl-up compared to rest. In women without DRA, the LA was least stiff closest to the umbilicus; it increased in stiffness during the head lift and curl-up, and did not distort or change in IRD.

CONCLUSIONS: DRA is associated with low LA stiffness and distortion during a semi-curl-up task; the amount of distortion is a function of both the IRD and LA stiffness.

Key words: linea alba, shear-wave elastography, inter-rectus distance, ultrasound imaging
INTRODUCTION

Diastasis recti abdominis (DRA) is a separation of the abdominal muscles in the midline and is seen in 33%-74% of women in the postpartum period. While a clinical diagnosis of DRA is made through palpation, inter-rectus distance (IRD) measured using B-mode ultrasound (FIGURE 1) is more precise, and has demonstrated excellent reliability and concurrent validity. IRD has thus been used to study the severity and impact of DRA in women.

While larger IRD has been associated with lower body image satisfaction and self-reported abdominal pain, the evidence for an association between IRD and motor impairment is less clear. Some authors have sought but found no evidence that IRD is associated with low back pain or impairment, while others have found impaired trunk flexion and rotation strength in women with DRA. In a recent cross-sectional study, we found that while women with DRA demonstrated impaired trunk rotation strength and capacity to perform a sit-up at one year post-partum, their isometric flexion force and trunk endurance were unaffected.

The ability of the linea alba (LA) to transmit forces across the midline may have a greater impact on function than the magnitude of the IRD. Lee & Hodges recently presented a new ultrasound measure, the distortion index, as a means of evaluating the contribution of the LA to load transfer. A LA that is intact and unstrained would presumably not distort during a curl-up because it is under tension. If the LA is not intact, however, the distortion index would theoretically be infinite as the fascia separates under tension. While the distortion index may provide insight into the functional impacts of DRA, it has not been validated against LA stiffness.
With recent advances in ultrasound imaging, tissue stiffness can be measured *in vivo* using shear-wave elastography\(^\text{14,21,25,26}\) (FIGURE 2b). This approach has good to excellent accuracy\(^\text{20,41}\) and good reliability when measuring muscle shear modulus at rest,\(^\text{21}\) under strain\(^\text{14,20,26}\) and during isometric contraction.\(^\text{3,4,14}\) Shear-wave elastography may help us to understand the biomechanical implications of DRA as well as the distortion index proposed by Lee\&Hodges.\(^\text{22}\)

The anatomy of the LA is heterogeneous along its length,\(^\text{11}\) and there is a lack of consistency around measurement sites and tasks used to evaluate DRA.\(^\text{39}\) Indeed, IRD has been found to have lower reliability\(^\text{16,19}\) and validity\(^\text{27}\) at sites below the umbilicus than above it. Further, a range of tasks has been used when measuring IRD.\(^\text{39}\) Understanding how measurement site or task difficulty influence measures relevant to DRA is important if we are to understand the functional implications of these outcomes.

The aims of this study were therefore to: 1) examine the impact of measurement site and task on morphological and biomechanical features of the LA in women with and without DRA; 2) investigate the two- and three-way linear relationships among IRD, LA stiffness and LA distortion, and 3) determine whether linear relationships between IRD, LA stiffness and LA distortion are different between women with and without DRA.

**METHODS**

The study was found to comply with the standards for the ethical conduct of research by the University of Ottawa Health Sciences and Sciences Research Ethics Board (H05-16-11), and all volunteers provided written informed consent before participating.

The sample size was determined *a priori* based on values reported by Lee \& Hodges,\(^\text{22}\) where, at \(\alpha=0.05\) and at 80% power, seven participants would be adequate to detect significant
differences in IRD between measurement sites \((\text{mean difference } (\bar{\text{diff}}) = 1.29, \text{ sd } = 0.77)\),
eight would be adequate to see differences in IRD between rest and the semi-curl-up task \((\bar{\text{diff}} = 1.19\text{mm, sd } = 0.77)\), and three would be adequate to detect differences in the distortion index
between women with and without DRA at the level of the umbilicus \((\bar{\text{diff}} = 0.069, \text{ sd } = 0.013)\).
Based on the reported correlation between IRD and the distortion index\(^{22}\), a sample of 19 was
estimated to be adequate to detect a moderate negative correlation \((r = -0.60)\).

**Participants**

Women were recruited via flyers placed at local recreational facilities and businesses in
the Ottawa-Gatineau region. Women were eligible to participate if they were nulliparous or had
delivered their most recent baby, vaginally, at least one year previously. Women were ineligible
if they reported being pregnant, having a history of abdominal, gynecological or urological
surgery, having a condition that could affect muscle contractility or lumbopelvic function, having
any respiratory dysfunction, or having a history of any pathology (e.g., fracture, surgery,
neoplasm) that could interfere with their capacity to perform the study tasks.

**Evaluator qualifications and training**

All imaging was performed by a physiotherapist with post-graduate training and over 400
hours of experience in B-Mode imaging of the muscles of the abdominal wall (NB). The
physiotherapist received 5 hours of training on shear-wave elastography at the LA by the senior
author (LM), and practiced image acquisition for >20 hours prior to data collection. The senior
author consulted during imaging when questions/difficulties arose.

**Procedure**

Women had their height, weight, waist and hip circumference measured using standard
procedures. They provided information on the number of pregnancies carried to term, the ages of
any children, and their habitual weekly amount of physical activity using a custom questionnaire.

Women were then positioned in supine on a plinth with their head resting on a thin pillow. A Supersonic™ Aixplorer ® Ultrafast™ ultrasound system (SuperSonic Imagine, Aix-en-Provence, France) interfaced with a 10-MHz linear transducer (Model SL15-4) was used. Imaging was done at three locations over the midline anterior abdominal wall: the superior border of the umbilicus, then 3cm and 5cm above this site, where measurement of IRD is reliable and valid (IRD measurements are less reliable and valid below the umbilicus). Three B-mode videos were captured concurrently with shear-wave elastography images at each location during each task (rest, head lift, semi-curl-up). There were two cases where the investigator was unable to visualize the entire width of the LA. In one case a curvilinear probe with a stand off pad was used, and in the other, panoramic imaging was used. All images were captured at end-exhalation, with breathing paused until after the images were captured. When performing the head lift, women kept their arms at their sides, paused their breathing at end-exhalation, gently lifted only their head off the pillow without altering their neck or spine posture, and held this position. When performing the semi-curl-up, women kept their arms at their sides, paused their breathing at end-exhalation, and lifted their head and shoulders until the inferior angles but not the spines of their scapulae remained in contact with the plinth. Positioning was verified and corrected by the physical therapist, and trials were repeated as necessary. During each task, the ultrasound video was captured until the desired position was achieved and held, while clear B-mode images and full shear-wave elastography colourmaps were obtained. The ultrasound probe was removed completely and was replaced after >60 seconds of rest was provided between trials and tasks.

**Data Processing**
The on-board software available on the Supersonic® Aixplorer™ ultrasound system was used for image processing. For each outcome, measurements were made for each of the three trials at each measurement site during each task. IRD was defined by the length of a straight line starting from the medial border of the hyperechoic fascia surrounding the hypoechoic rectus abdominis muscle on one side and ending at the medial border of the hyperechoic fascia on the opposite side. Participants were classified as having DRA based on Hills et al. if IRD > 2.2 cm at 3 cm above the umbilicus AND mean IRD > 2.2 across the three measurement sites.

The distortion index was calculated as described by Lee & Hodges; the area enclosed by the traced path of the LA (FIGURE 2c) and the IRD was divided by the IRD. Where the LA distorted anteriorly, the anterior boundary of the fascia was traced, whereas where the LA distorted posteriorly (e.g. FIGURE 2c), the posterior boundary was traced. Tissue stiffness was calculated within a region, drawn freehand, bounded by the superficial and deep borders of the LA (FIGURE 2d). The software automatically computed mean and peak stiffness, in kilopascals (kPa), within this bounded area, and both values were retained for analysis.

Image analysis was performed by two MSc physiotherapy students (EN, NG) who received hands-on training by the study senior investigator (LM, 10 hours) and by the study physiotherapist (NB, 10 hours). The students practiced the image analysis independently (10 hours each) while analyzing images unrelated to this study. They then compared their results and discussed discrepancies prior to beginning image analysis for the current study. The two raters independently analyzed images to generate IRD, distortion index and mean and peak LA stiffness from each video clip while blinded to participant demographic data, clinical examination findings, and each other’s results.
Model 3 Intraclass Correlation Coefficients (ICCs) were used to evaluate within- and between-rater reliability of all ultrasound outcomes. The within-rater reliability was adequate for IRD (ICC=0.965-0.983) and for mean (ICC=0.868-0.913) and peak (ICC = 0.721-0.901) LA stiffness recorded across the three tasks, while it was lower for the distortion index, ranging from ICC=0.433 to ICC=0.869. The between-rater reliability was adequate for IRD (ICC 0.944-0.955) and for mean (ICC=0.981-0.994) and peak (ICC= 0.979-0.996) LA stiffness, but was more moderate for the distortion index (ICC = 0.746 to 0.766). In three cases (mean LA stiffness at rest, distortion index on head lift and on semi-curl-up), the within-rater ICCs were significantly (t-test at \( \alpha=0.05 \)) higher for Rater 2 than for Rater 1, therefore the values obtained by Rater 2 were retained for analysis.

**Data Analysis**

Statistical analyses were performed using IBM SPSS Statistics Version 24 (IBM Corporation, Armonk, NY); \( \alpha=0.05 \) was used for all hypothesis testing. Data were tested for normality using the Shapiro-Wilk test.

The impact of DRA status, measurement site (at, 3cm and 5 cm above the superior border of the umbilicus) and task (rest, head lift, semi-curl up) was tested separately for each primary outcome (IRD, mean and peak LA stiffness, distortion index), using repeated-measures analyses of variance models which included all two- and three-way interactions. Bonferroni corrections were used where indicated.

Linear regression analyses were used to determine the relationships among IRD at rest, IRD during head lift and IRD during semi-curl-up, and between mean and peak LA stiffness to evaluate potential redundancies and collinearity in subsequent models. Based on the results,
univariate regressions between IRD and LA stiffness and between IRD and LA distortion were computed using only IRD at rest. In each model, the outcome was the mean value across the three trials recorded at each of the three measurement sites, the strength of the relationship was evaluated using the correlation coefficient (R), model significance (p), model variance (R²), normality of the residuals and the relationship between residuals and fitted values. Each model was computed for the whole dataset, then with the sample separated by cohorts (with/without DRA). A multivariate regression analysis was then used to evaluate the combined effect of IRD and peak LA stiffness on the distortion index recorded during the semi-curl up.

Secondary analyses using covariate (ANCOVA) models investigated the effect of demographic factors including parity (yes, no), age, waist-hip ratio, and physical activity level on the primary outcomes.

RESULTS

Sample characteristics

Twenty women participated; demographic data are reported in TABLE 1.

The impact of DRA status, measurement site and task

All primary outcomes were normally distributed and are summarized in TABLE 2. There were significant interaction effects among DRA status, measurement site and task (FIGURE 3). For IRD, there was no significant 3-way interaction, but there was a DRA status by site interaction (F=4.31, p=0.014) and a DRA status by task interaction. While women with DRA had larger IRDs than those without DRA, and they demonstrated no effect of measurement site on their IRD, they demonstrated a reduction in their IRD on the semi-curl-up compared to rest.
whereas the women without DRA did not. The women without DRA had larger IRDs at the superior border of the umbilicus than at 3cm above the umbilicus.

For the distortion index, there was a 3-way interaction between DRA status, site and task. Using pairwise comparisons, fixing task, there was no DRA status by site interaction (F=1.48, p=0.229). Fixing DRA status, there was a site by task interaction (F=3.27, p=0.038). Fixing site, there was a significant DRA status by task interaction (F=4.28, p=0.014). At all sites, women with DRA had more LA distortion than women without DRA, and the women with DRA demonstrated more distortion on the semi-curl-up than at rest (FIGURE 3b) while the women without DRA demonstrated no difference in distortion among tasks.

The results were similar between mean and peak LA stiffness. There was no 3-way interaction, and there was no 2-way interaction between DRA status and measurement site (F=1.25, p=0.288; F=0.93, p=0.395), but there were interactions between DRA status and task (F=44.05, p<0.001; F=26.35, p<0.001) and between site and task (F=3.49, p=0.008; F=3.03, p=0.017). The women without DRA experienced the greatest stiffness in their LA during the semi-curl-up and the lowest stiffness in their LA at rest, while the women with DRA did not experience any increase in mean or peak stiffness in their LA during the head lift or the semi-curl-up compared to rest (FIGURE 3c and d; FIGURE 4). Among women in both groups, during the semi-curl-up, the mean and peak LA stiffness was lower at the superior border of the umbilicus that it was as the other sites.

**Relationships amongst IRD, LA distortion and LA stiffness**

A strong, positive, linear relationship was found between IRD measured during both the head lift (r=0.971, R²=94.3%, slope=0.878cm/cm, intercept=0.170cm, p<0.001), and the semi-curl-up (r=0.944; R²=89.1%, slope=0.745cm/cm, intercept = 0.421cm 4, p<0.001; FIGURE 5a)
compared to at rest. Positive, linear relationships were also found between mean and peak LA stiffness (FIGURE 5b). At rest and during the head lift, the linear regression models were significant ($R^2=62.3\%$; $p<0.001$, $R^2=71.2\%$, $p<0.001$ respectively), with slopes of $1.65\text{kPa/kPa}$ at rest and $1.69\text{kPa/kPa}$ during the head lift. The model was strongest during the semi-curl-up ($R^2=79.3\%$, $p<0.001$) with a slope of $1.51\text{kPa/kPa}$. Measurement site did not significantly affect the linear regressions between peak and mean LA stiffness.

At rest, there was a moderate negative univariate association between IRD and mean LA stiffness while the univariate relationship between IRD and peak LA stiffness was not significant (TABLE 3). During the semi-curl-up, the univariate relationships between IRD and both mean and peak LA stiffness produced a good fit with the data.

Larger IRDs were associated with more LA distortion (TABLE 3) in the women with DRA (FIGURE 5c); the linear regression models were substantively similar regardless of whether the women were at rest, or were performing a head lift or a semi-curl-up.

When the univariate relationships between IRD and LA stiffness and distortion were investigated separately by cohort (TABLE 3), the regressions remained significant, with similar model parameters ($R$, $R^2$, slope) for the women with DRA as was seen when all data were combined. In contrast, the regressions were not significant for the women without DRA.

The univariate relationships between LA distortion and mean and peak LA stiffness were moderate when recorded at rest; higher distortion indices were associated with lower stiffness (TABLE 3). These relationships were stronger for the head lift and semi-curl-up, and were relatively unaffected by DRA status (FIGURE 5d).

Because of the collinearity between mean and peak LA stiffness, for the multivariate model, we chose to include only peak LA stiffness during the semi-curl up, as it produced the
strongest correlation with the mean stiffness, and the widest range of values. Using distortion index during the semi-curl-up as the dependent variable and IRD recorded at rest and peak LA stiffness recorded during the semi-curl-up as independent variables, the regression was significant ($F_{2,17}=43.66$, $p<0.001$). There was no two-way interaction between IRD and LA stiffness. The model fit the data well, resulting in an adjusted $R^2$ value of 81.79% and with both IRD ($F_{1,17}=37.13$, $p<0.001$) and LA stiffness ($F_{1,17}=5.17$, $p=0.036$) contributing significantly to the model fit:

$$Distortion = -0.043 + 0.3261 \times IRD - 0.00279 \times stiffness$$

This model fit the data slightly better than the univariate regressions presented in TABLE 3.

Including cohort in the model resulted in no significant interaction effects between cohort and either independent variable, and, while there was a marginal cohort main effect ($F_{1,16} = 4.10$, $p=0.06$), including cohort in the model did not produce a regression that fit the data (adjusted $R^2 = 84.59\%$) substantively better than the multivariate regression computed without cohort.

**The effect of participant demographic characteristics on IRD, LA distortion and LA stiffness**

There were no significant two-way interactions between task, age, parity, waist-hip ratio, or self-reported habitual amounts of physical activity for any of the study outcomes. Older women presented with larger IRDs ($p<0.001$) and less LA distortion ($p=0.008$) than younger women. Parity was associated with lower mean ($p=0.015$) and peak ($p=0.017$) LA stiffness, but because of the small sample, and the substantive collinearity ($r>0.70$, $p<0.01$) between age, parity and DRA in our sample, we did not include these demographic factors in the linear regression analyses.

**DISCUSSION**
The main findings of this study were that women with DRA demonstrated lower LA stiffness and more LA distortion across all tasks and measurement sites compared to women without DRA. Among women without DRA, the head lift and semi-curl up resulted in progressively higher stiffness in the LA, regardless of measurement site, and the LA did not distort. In contrast, among women with DRA the LA distorted along its length, and did not become stiffer during the head lift or semi-curl-up. These results suggest that there are both morphological and mechanical alterations in the LA among women with DRA.

**Inter-rectus distance**

Although small differences were found when IRD was measured in women with DRA when they performed the different tasks, the regression analyses suggest that IRD need not be measured at multiple sites nor during a head lift or a semi-curl-up. The between-rater ICCs for IRD at rest and during the semi-curl-up were consistent with published data. The change in IRD seen during the head lift and semi-curl-up was consistent with recent reports by Mota and colleagues and with Lee & Hodges who reported that the LA narrowed during a curl-up task when no instruction was given about how to perform the task. The underlying cause of this narrowing is unknown but may be an artifact of the measurement procedure (the muscle bellies of the rectus abdominis may approximate due to increased bulk when contracting).

**LA stiffness**

While shear-wave elastography has been used for musculoskeletal applications, to our knowledge, this is the first application of shear-wave elastography to study DRA. Measures of LA stiffness appear to be sensitive to tissue anisotropy, task, and DRA status. As such, measurement site and task were more relevant to LA stiffness than to IRD; stiffness was consistently highest during the semi-curl-up task and was consistently lowest at the superior
border of the umbilicus. LA stiffness appears to have excellent reliability both between and
within raters.

In the women with DRA, larger IRDs were associated with lower LA stiffness,
presumably because larger IRDs reflect greater tissue strain.39 The univariate linear regression
models between IRD and LA stiffness accounted for less than half of the variance in the data,
and were only significant among women with DRA. These findings support the hypothesis put
forward by Lee & Hodges,22 that the mechanical impact of DRA may be as or more relevant to
function than the IRD, and may explain why authors have failed to consistently detect
impairments associated with DRA.17,29 As illustrated in FIGURE 4, our results support the use of
shear-wave elastography to investigate LA biomechanical function, and the relationships
between LA stiffness and lumbopelvic function and the impact of rehabilitation interventions.

**LA distortion**

LA distortion at rest may not have adequate reliability for the evaluation of DRA, but
may be more reliable during the semi-curl-up. Our findings also suggest that the semi-curl-up,
but not the head lift, as is typically used for assessment of the IRD39 provides adequate challenge
to see LA distortion. In the women without DRA, there was little distortion of the LA, likely
because the intact LA is taut due to the tensile forces generated by the muscles of the lateral
abdominal wall. In some women with DRA, the LA was distorted even at rest (FIGURE 4e), and
this distortion increased during the head lift and semi-curl-up (FIGURE 4g), possibly reflecting a
substantive rupture of the LA (e.g. in FIGURE 4e there appears to be a complete rupture of the
attachment of the LA on the left side). Reducing LA distortion during functional tasks may
indeed be an objective for rehabilitation.

**Relationships among IRD, LA stiffness and LA distortion**


Both LA stiffness and LA distortion behaved as expected; when IRD was large, LA stiffness was lower and LA distortion was higher- and the univariate relationships were strongest during the semi-curl-up. The relationships between IRD and LA distortion were stronger than those between IRD and stiffness. While the linear relationships between IRD and LA stiffness were significant, other factors besides the IRD, such as damage to other aspects of the abdominal musculature and sheaths, may influence the capacity of the LA to generate tensile force and may account for some of the unexplained variance in the model. This is an area for future investigation.

The range of IRDs (0.79 to 4.96cm) in this study was larger than that reported in Lee & Hodges and may explain the stronger regression found here. More LA distortion was seen in women with DRA, particularly among those who generated less LA stiffness during the semi-curl-up. Understanding this multivariate relationship may be useful when evaluating the functional impacts of DRA as well as changes in the biomechanical function of the LA induced through rehabilitation interventions. In particular, a wide IRD may not be functionally problematic if the LA still stiffens when a task demands load transfer across the midline. Some women with DRA in our sample, particularly those with 2.2cm<IRD <3cm, generated high stiffness in their LA during the semi-curl-up task, with values similar to those seen in women without DRA(Figure 5d). It is quite plausible that this subgroup of women with “mild” DRA have no difficulty with functional task performance. Conversely, the women with high LA distortion (distortion index>0.50cm) all had DRA and all generated low (< 50kPa) peak stiffness in their LA during the semi-curl-up (Figure 5c). These data suggest that we may be able to predict functional impairments based on a combination of IRD, LA stiffness and/or LA distortion, and support the implementation of such a study as a logical next step.
Limitations

Before shear-wave elastography or the distortion index are used in a clinical context, full reliability analyses are essential. Shear-wave elastography methods may be limited when women have large IRDs because the field of view is limited to the width of the probe. While panoramic impaging is and option, it was challenging to get stable shear-wave elastography colourmaps using panoramic imaging during dynamic tasks.

The results of the secondary analysis suggest that both age and parity may independently influence the structure and function of the LA. Specifically, it appears that women who are older have larger IRDs and demonstrate more LA distortion. Parity, however, appears to influence the stiffness of the LA, regardless of age, suggesting that stresses on the LA during pregnancy produce lasting strain. This result should be interpreted with caution, however as the sample was small and there was a significant correlation between age and parity (r=0.746, p=0.000) which may reflect a recruitment bias- older volunteers tended to be parous and to have DRA. While not conclusive, this finding does provide impetus for future research to evaluate the interactions among age, DRA and parity on the structure and mechanical function of the LA in women.

CONCLUSION

Our results support further research on the influence of LA distortion and LA stiffness in evaluating the biomechanical implications of DRA. While IRD and LA distortion appear to be uninfluenced by measurement location, the stiffness of the LA is not uniform along its length and as such may need to be measured at multiple sites. Our results also confirm that LA distortion observed during a semi-curl-up is a reflection of both the morphology and stiffness characteristics of the LA and that LA distortion may best be measured during a semi-curl-up and
not a head lift. While LA distortion, computed through B-mode imaging, is more clinically accessible than quantitative shear-wave elastography, it should not be interpreted as a direct reflection of the extent to which the LA stiffens.

KEY POINTS

FINDINGS: Among women with DRA, while IRD is not significantly affected by measurement site or task, LA stiffness is significantly affected by both of these factors, and LA distortion is affected by the difficulty of the task. Both LA stiffness and IRD are significant predictors of how much the LA distorts during a semi-curl-up task when women have DRA.

IMPLICATIONS: Shear-wave elastography may have utility in the development of best-practice recommendations for women with DRA. A capacity to stiffen the LA may be a good predictor of function and this is an important next step for this research.

CAUTION: We do not yet know the implications of LA stiffness or distortion on the symptoms nor functional abilities of women with DRA.
REFERENCES


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<tr>
<th>Characteristics</th>
<th>n=20</th>
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<tr>
<td>Age (years)</td>
<td>31 (8)</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>25.28 (3.89)</td>
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<td>Waist to hip ratio</td>
<td>0.80 (0.05)</td>
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<td>Minutes of Moderate-Vigorous Physical Activity per week</td>
<td>144 (110)</td>
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<td>- 0</td>
<td>9 (45%)</td>
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<tr>
<td>- 1</td>
<td>1 (5%)</td>
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<td>- 2</td>
<td>9 (45%)</td>
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<td>- 3</td>
<td>1 (5%)</td>
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Abbreviations: BMI, body mass index; SD, standard deviation. Data are mean (SD) or Numbers with percentages (%).
TABLE 2. Inter-rectus distance, mean and peak linea alba stiffness and linea alba distortion recorded from n=20 women

<table>
<thead>
<tr>
<th>SITE</th>
<th>INTER-RECTUS DISTANCE (cm)</th>
<th>MEAN STIFFNESS (kPa)</th>
<th>PEAK STIFFNESS (kPa)</th>
<th>DISTORTION INDEX (UNITLESS)</th>
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<tr>
<td>REST</td>
<td>SBU</td>
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<td>30.49†* (18.42)</td>
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<td></td>
<td>3SBU</td>
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<td>27.00†* (14.76)</td>
<td>41.94* (29.88)</td>
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<td></td>
<td>5SBU</td>
<td>2.54 (1.45)</td>
<td>35.21††* (17.91)</td>
<td>52.59††* (30.66)</td>
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<td>55.54†*** (51.43)</td>
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<tr>
<td></td>
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<td>2.47 (1.39)</td>
<td>36.28†*** (27.50)</td>
<td>62.21** (54.29)</td>
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<tr>
<td></td>
<td>5SBU</td>
<td>2.43 (1.33)</td>
<td>40.97††*** (30.20)</td>
<td>65.76††*** (58.79)</td>
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<td>SEMI CURL-UP</td>
<td>SBU</td>
<td>2.27 (1.15)</td>
<td>36.14†*** (29.95)</td>
<td>64.86†*** (55.91)</td>
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<td>3SBU</td>
<td>2.30 (1.15)</td>
<td>46.87†*** (37.52)</td>
<td>79.64*** (62.16)</td>
</tr>
<tr>
<td></td>
<td>5SBU</td>
<td>2.36 (1.00)</td>
<td>50.45†*** (37.00)</td>
<td>85.14†*** (61.45)</td>
</tr>
</tbody>
</table>

All values are presented as mean (standard deviation). Image sites were the superior border of the umbilicus (SBU), 3 cm above the superior border of the umbilicus (3SBU) and 5 cm above the superior border of the umbilicus (5SBU). Significant differences in outcomes between tasks are indicated, whereby outcomes measured during tasks marked with * are significantly different from those measured during tasks marked with **, and outcomes measured during tasks marked with *** are significantly different from outcomes measured during tasks marked with †. Similarly, outcomes at sites marked with † are significantly different from those at sites marked with ††.
<table>
<thead>
<tr>
<th>Regressions</th>
<th>IRD range</th>
<th>R</th>
<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
<th>p-value</th>
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<tbody>
<tr>
<td><strong>IRD SCU vs IRD rest</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>All data</td>
<td>0.966</td>
<td>0.933</td>
<td>0.8</td>
<td>0.38</td>
<td>&lt;0.001*</td>
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<tr>
<td>IRD &lt;2.2cm</td>
<td>0.135</td>
<td>0.02</td>
<td>0.40</td>
<td>0.12</td>
<td>0.750</td>
<td></td>
</tr>
<tr>
<td>IRD &gt;2.2cm</td>
<td>0.894</td>
<td>0.80</td>
<td>0.55</td>
<td>1.01</td>
<td>&lt;0.001*</td>
<td></td>
</tr>
<tr>
<td><strong>Mean stiffness at rest vs IRD rest</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All data</td>
<td>-0.601</td>
<td>0.362</td>
<td>-8.05</td>
<td>52.38</td>
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<td>0.01</td>
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<td>0.35</td>
<td>-7.97</td>
<td>51.53</td>
<td>0.044*</td>
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<tr>
<td><strong>Peak stiffness at rest vs IRD rest</strong></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>All data</td>
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<td>-11.16</td>
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<tr>
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<td>0.37</td>
<td>-21.37</td>
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<tr>
<td><strong>Mean LA stiffness during SCU vs IRD rest</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All data</td>
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<td>0.428</td>
<td>-17.35</td>
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</tr>
<tr>
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<td>-10.59</td>
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<td>-20.09</td>
<td>102.0</td>
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<tr>
<td><strong>Peak LA stiffness during SCU vs IRD rest</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>-25.17</td>
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<td>47.71</td>
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<tr>
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<td>-37.52</td>
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<tr>
<td><strong>Mean LA Stiffness during SCU vs DI</strong></td>
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<td>-34.69</td>
<td>64.16</td>
<td>0.015*</td>
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<tr>
<td><strong>Peak LA Stiffness during SCU vs DI</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All data</td>
<td>-0.694</td>
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<td>-67.78</td>
<td>118.0</td>
<td>0.001*</td>
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</tr>
<tr>
<td>IRD &lt;2.2cm</td>
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<td>0.60</td>
<td>-460.0</td>
<td>181.0</td>
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<tr>
<td>IRD &gt;2.2cm</td>
<td>-0.712</td>
<td>0.52</td>
<td>-64.71</td>
<td>116.0</td>
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<tr>
<td><strong>DI vs IRD rest</strong></td>
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<tr>
<td>All data</td>
<td>0.887</td>
<td>0.787</td>
<td>0.40</td>
<td>0.44</td>
<td>&lt;0.001*</td>
<td></td>
</tr>
<tr>
<td>IRD &lt;2.2cm</td>
<td>0.135</td>
<td>0.02</td>
<td>0.04</td>
<td>0.12</td>
<td>0.750</td>
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</tr>
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<td>1.01</td>
<td>&lt;0.001*</td>
<td></td>
</tr>
<tr>
<td><strong>DI vs IRD during SCU</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>All data</td>
<td>0.874</td>
<td>0.764</td>
<td>0.47</td>
<td>0.57</td>
<td>&lt;0.001*</td>
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<tr>
<td>IRD &lt;2.2cm</td>
<td>0.689</td>
<td>0.48</td>
<td>0.17</td>
<td>0.08</td>
<td>0.059</td>
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<tr>
<td>IRD &gt;2.2cm</td>
<td>0.857</td>
<td>0.73</td>
<td>0.64</td>
<td>1.12</td>
<td>&lt;0.001*</td>
<td></td>
</tr>
</tbody>
</table>
Each regression is presented for the sample as a whole (n=20) then by Diastasis recti abdominis (DRA) cohort defined by an IRD>2.2cm at 3cm above the umbilicus AND a mean IRD>2.2cm. Abbreviations: IRD, inter-rectus distance; LA, linea alba; DI, distortion index; SCU, semi curl-up. * denotes significant regressions.
An image of the linea alba in a nulliparous woman positioned in supine and at rest acquired using the Supersonic™ Aixplorer® ultrasound system coupled with a high frequency (10MHz) linear probe (Model SL15-4). Left panel: B-mode ultrasound image. Right panel: Same image with tissues labelled. RA = rectus abdominus, LA = linea alba. SC = subcutaneous fatty layer. The red arrow indicates the inter-rectus distance (IRD).
FIGURE 2: Measurement of Linea Alba Distortion I and Linea Alba Stiffness

a) B-mode image of the linea alba in a woman with diastasis recti abdominis. b) Shear wave elastography colour map acquired in the region of the linea alba in a nulliparous woman without diastasis recti abdominis (corresponding B-mode image in panel d below). c) Same image as in a, where the green line denotes the inter-rectus distance while the yellow line indicates the posterior boundary of the linea alba. These lines generate the area used in the numerator in the calculation of the distortion index. d) B-mode image of the linea alba recorded concurrently with the shear-wave elastography colourmap in panel b. The blue region indicates the region of interest traced by the user to reflect the borders of the linea alba. The mean and peak stiffness values within this region, determined by the on-board software of the Supersonic Aixplorer Ultrafast Ultrasound system, were used as outcome measures in the analysis.
FIGURE 3: Cohort, measurement site and task effects on Inter-Rectus Distance, Distortion Index and Linea Alba Stiffness.

Inter-rectus Distance (a), Distortion Index (b), Mean Linea Alba Stiffness (c) and Peak Linea Alba Stiffness (d) are plotted by cohort, measurement site and task. Abbreviations: DRA = diastasis recti abdominis, HL = head lift maneuver, SCU = semi-curl-up maneuver, SBU = superior border of the umbilicus, 3SBU = 3 cm above the superior border of the umbilicus, 5SBU = 5 cm above the superior border of the umbilicus. Significant differences were tested at \( \alpha = 0.05 \) with Bonferroni correction applied. Significant cohort effects are indicated by *. Significant measurement site effects are indicated by ‡. Significant task effects are indicated by †.
FIGURE 4: Sample of linea alba morphology and stiffness images derived from shear wave elastography (SWE) ultrasound imaging.

B-mode images of the linea alba are indicated on the left panels with corresponding shear-wave elastography images immediately to the right in each case. The legend at the top right shows that areas of low stiffness are represented by blue, with progressively higher stiffness represented by warmer colours ranging from turquoise to yellow to red. The upper four panels (a-d) are images of the linea alba recorded from a nulliparous woman with no diastasis recti abdominis (DRA), a and b were acquired at rest and c and d were acquired during a semi-curl-up. The lower four panels (e-h) are images of the linea alba acquired from a parous woman who met the study criteria for DRA, while she was at rest (e,f) and performing a semi-curl-up (g,h). Note the high stiffness of the linea alba when the nulliparous woman performed the semi-curl-up (d), where peak stiffness reached 118kPa. In the parous woman, note the larger inter-rectus distance (2.63cm) at rest (e) and the posterior distortion of the linea alba during the semi-curl-up (g) where there was no apparent increase in linea alba stiffness (h).
FIGURE 5. Scatter plots and trend lines for outcome measures

a) Scatter plot of inter-rectus distance (IRD) recorded at rest vs. IRD recorded during a head lift (red) and semi-curl-up (blue).  
b) Scatter plot of mean vs peak linea alba stiffness recorded at rest (blue), during a head lift (green) and during a semi-curl-up maneuver (red).  
c) Scatter plot of IRD recorded at rest and linea alba distortion measured during a semi-curl-up maneuver. The women without diastasis recti abdominis are indicated in blue, while those with diastasis recti abdominis are indicated in red.  
d) Scatter plot of the distortion index vs peak linea alba stiffness recorded during a semi-curl-up. Women without diastasis recti abdominis are indicated in blue while those with diastasis recti abdominis are indicated in red. Note that the regression line for women without diastasis recti abdominis (blue) is not significant.