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Faculdade de Motricidade Humana

Morphological and functional adaptations of the abdominal wall during pregnancy and in the postpartum period

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Para as minhas filhas, Maria Miguel e Mercedes,
Por fazerem querer superar-me todos os dias,
Com todo o meu amor.

To my daughters, Maria Miguel and Mercedes,
For bringing out the best of me everyday,
With all my love.

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Adaptações morfológicas e funcionais da parede abdominal durante a gravidez e pós-parto

Resumo

A diástase dos retos abdominais (DRA) carateriza-se pela separação dos músculos rectos abdominais, sendo que o incremento da distância inter-rectos (DIR) se inicia durante a gravidez e prolonga-se pelo puerpério. A fiabilidade dos instrumentos de registo desta condição é reduzida sendo escasso o conhecimento sobre a prevalência e factores de risco que lhe estão associados. Adicionalmente existe pouca evidência sobre o efeito na prevenção e/ou agravamento da DIR induzida pelos trabalho abdominal.

Assim, foram objetivos desta tese 1) o desenvolvimento de uma metodologia fiável de avaliação da morfologia da parede abdominal feminina; 2) descrição da prevalência da DIR, factores de risco e relação com dor lombo-pélvica aos 6 meses no pós-parto; 3) e avaliar a resposta imediata da DIR ao exercício, nomeadamente no *crunch* abdominal e no *drawing-in*.

Cento e oitenta e sete mulheres participaram nos cinco estudos apresentados na tese. Os resultados dos três estudos metodológicos demonstraram a fiabilidade da medição da DIR com base na ultrassonografia, nomeadamente face à palpação. Nos dois estudos longitudinais foi avaliada a prevalência e potenciais fatores de risco da DRA a par da associação do incremento de DIR com a incidência de dor lombo-pélvica assim como o efeito imediato dos exercícios *crunch* e *drawing-in*.

Os resultados revelaram que aos 6 meses de pós-parto a DRA tem uma prevalência de 39% não apresentando relação significativa com a dor lombo pélvica. A resposta imediata produzida pelo exercício *drawing-in* foi um aumento da DIR, enquanto o *crunch* induziu a redução imediata da DIR, tanto na gravidez como no pós-parto.

Palavras-chave:

Diástase Abdominal, Fiabilidade, Ultrassom, Exercício, Biomecânica.

Morphological and functional adaptations of the abdominal wall during pregnancy and in the postpartum period

Abstract

Diastasis recti abdominis (DRA) or increased inter rectus distance (IRD) is characterized by the separation of the rectus abdominis muscles. It has its onset during pregnancy and the first weeks following childbirth. The reliability of the instruments used to assess this condition is unclear. There is scant knowledge on the prevalence and risk factors for development of the condition. There is little evidence on which exercises are most effective in reduction of DRA.

The aims of the present thesis were to establish a reliable method for the assessment of the morphology of the abdominal wall, describe the natural recovery of IRD from late pregnancy till 6 months postpartum and evaluate IRD during drawing in and abdominal crunch exercises.

One hundred and eighty-seven women participated in the different studies comprising this thesis. The results of the three methodological studies showed ultrasound imaging to be a reliable method for measuring IRD. Palpation has sufficient reliability to be used in clinical practice. However, ultrasound is a more accurate and valid method. The ultrasound transducer can be held relatively stationary in a clinical setting, to evaluate IRD.

DRA is prevalent at 6 months postpartum, with a prevalence rate of 39% but is not linked with lumbo-pelvic pain.

The drawing in exercise widened the IRD in postpartum women while the abdominal crunch narrowed the IRD compared to rest both during pregnancy and in the postpartum period.

Keywords:

Diastasis, Reliability, Ultrasonography, Exercise, Biomechanics.

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List of Abbreviations

- AC = Abdominal Crunch
- AU = Above the Umbilicus
- BU = Below the Umbilicus
- CI = Confidence Intervals
- DI = Drawing-In
- DRA = Diastasis Recti Abdominis
- DP = Different Parity women
- $ICC_{1,1}$ = Intra Class Correlation one way random effect model (95% confidence interval)
- IRD = Inter-Rectus Distance
- MDC_{95} = Minimum Detectable Change at the 95% confidence level
- Mean diff = Mean difference between groups and confidence intervals.
- OR = Odds Ratio
- PP = Post-Partum women
- RT = Rest
- SEM = Standard Error of Measurement

Chapter I

General Introduction

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Preview

Pregnancy and becoming a mother is one of the most exciting times in a women's life. Besides all the hormonal and physiological changes affecting women during this period, probably the most obvious morphological alteration during pregnancy is the increasing weight and dimensions of the uterus, influencing maternal trunk musculoskeletal morphology, particularly the abdominal musculature. Many women continue or even begin to exercise during pregnancy, and postnatal women are encouraged to resume abdominal exercises shortly after delivery, to restore their abdominal figure and fitness. There is a lot of information available in numerous web pages about exercise programs for women during pregnancy and in the postpartum period, and physiotherapists and exercise instructors prescribe exercises to this population everyday. However, there is little evidence available about muscular changes and the effect and safety of different abdominal exercises during and after pregnancy.

Diastasis recti (DRA) or the increased inter–rectus distance (IRD) seems to be a common condition in women during pregnancy and postpartum. The lack of evidence for the consequences of this condition and the effect of abdominal strengthening exercises in the reduction of DRA indicates a need for identification of prevalence and risk factors of DRA. Use of responsive, reliable and valid outcome measures is mandatory for evaluation of the condition, and ultrasound imaging has recently been suggested as a useful method to assess muscular geometry and to quantify DRA. However, its reliability and validity must first be tested. The overall aim of this thesis was to establish the reliability of ultrasound measurements to assess IRD, to identify the prevalence and risk factors of DRA, and to evaluate the effect of two different abdominal contractions on IRD during pregnancy and postpartum period.

In this chapter, the background of this thesis is presented as well as the main goals and overview for each of the 5 studies presented in chapters II to VI. Some important methodological considerations are also provided.

1. Background

1.1 Anatomy of the abdominal muscles and their aponeuroses

The anterolateral wall of the abdomen has a laminar configuration composed by six layers including, from surface to depth, the skin, the superficial fascia, fat, the abdominal muscles, the transversalis fascia and the parietal peritoneum. The muscular layer comprise four paired muscles with fibers oriented vertically (rectus abdominis muscle), obliquely (external and internal oblique muscles) and horizontally (transversus abdominis muscles) with skeletal attachments on the thoracic cage, pelvis and the spinal column via the thoracolumbar fascia (Standring, 2008). The aponeuroses of these muscles represent sheet-like tendons that form the sheath of the rectus abdominis (rectus sheath) and also serve as the medial insertion of the oblique's and transversus muscles, along the anterior midline of the abdomen, forming a fibrous structure that connect the right and the left side of the abdominal wall, the linea alba (Fig. I-1).

The rectus abdominis (RA) and the pyramidalis are the only vertical muscles in the abdominal wall. The rectus abdominis muscle originates from the 5th through 7th costal cartilages to insert on the symphysis pubis and crest. Superiorly, the rectus is wide, broad, and thin, becoming narrow and thick inferiorly (Kahle, Leonahardt, & Platzer, 1991). Segmentation of each rectus muscle occurs by tendinous intersections that represent attachment of the rectus muscle with the anterior layer of the rectus sheath.

The two RA muscles are separated by the linea alba and each one is invested within a sheath derived from the aponeuroses of the deepest abdominal muscles (Standring, 2008). The rectus sheath consists of an anterior and a posterior layer (lamella) formed by the aponeuroses of the external and internal oblique and transversus abdominis muscles. These aponeuroses meet at the lateral edge of the rectus along a curved line to form the linea semilunaris, which extends from the 9th costal cartilage to the pubic tubercle. Above the umbilicus the anterior and posterior sheaths are composed by the aponeuroses from the internal oblique muscle. In effect, the internal oblique aponeurosis splits, allowing one layer to pass anterior and one posterior to the rectus muscle. The anterior wall of the rectus sheath includes also the external oblique aponeurosis and the posterior sheath consists of contributions from aponeuroses of the transversus abdominis (transversalis fascia). Inferior to the umbilicus, approximately halfway between the umbilicus and the symphysis pubis, the external abdominal aponeurosis has no contribution to the formation of the posterior rectus sheath and all three aponeuroses pass anterior to the rectus muscle. This anterior displacement of the aponeuroses creates a curved line of demarcation, in the posterior lamella of the rectus sheath, called the arcuate line, below which only the transversalis fascia separates the rectus abdominis muscle from the parietal peritoneum (Fig. I-1).

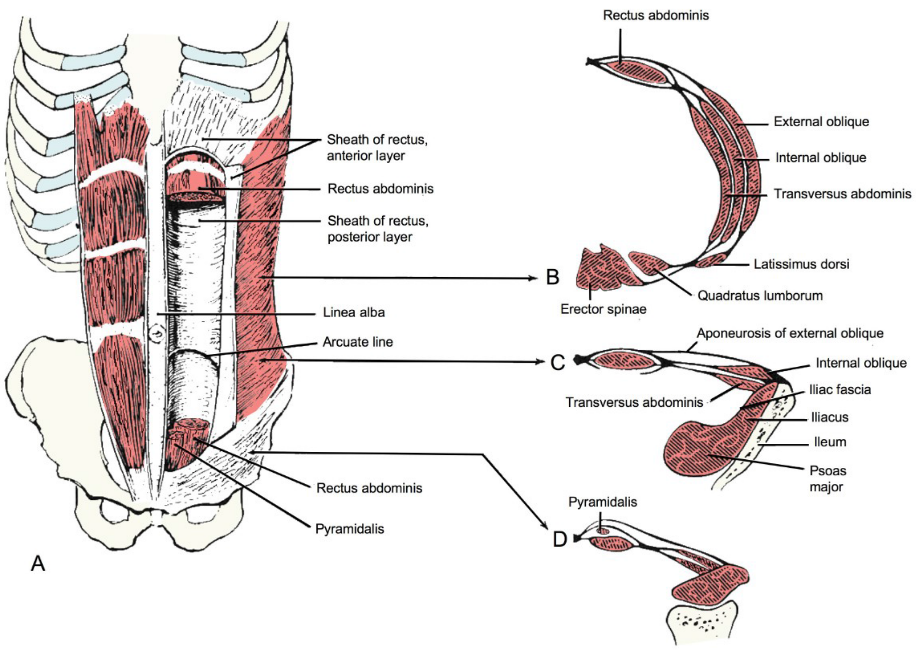

Fig. I-1. Abdominal muscles and their aponeuroses. **A** The rectus abdominis.
B, **C** and **D** shows a common arrangement of the sheath as seen in horizontal section.

In O'Rahilly, Muller, Carpenter & Sweson (1983). "Basic Human Anatomy". Reprinted with permission from http://www.dartmouth.edu/~humananatomy/figures/chapter_25/25-6.HTM. A technical support from Dartmouth Medical School, Hanover, United States of America.

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The linea alba reaches from the xiphoid process to the pubic symphysis and is defined as the fusion of the aponeuroses of the deepest abdominal muscles (Beer et al., 2009). The linea alba consists of a three-dimensional, highly structured meshwork of collagen fibers (Axer, Keyserlingk, & Prescher, 2001) which in conjunction with both rectus sheaths are regarded as the most important structures for the stability of the abdominal wall from a mechanical point of view (Axer et al., 2001; Grässel, Prescher, Fitzek, Keyserlingk, & Axer, 2005; Hernández-Gascón et al., 2012). The linea alba tension is important to maintain the abdominal muscles, particularly the rectus muscles, at a certain proximity to each other (Beer et al., 2009; Rath et al., 1996) in order to optimize abdominal muscles function both as on abdominal viscera support or producing thorax/pelvis movements.

Tension on the linea alba, particularly below the umbilicus, seems to be regulated by the pyramidalis, a small paired triangular-shaped muscle, present in 80% of people , which lies between the anterior surface of the rectus abdominis and the posterior surface of the rectus sheath (Lovering & Anderson, 2008). The precise function of the pyramidalis muscles is unclear, but together both muscles are thought to assists in tensing the linea alba (Lovering & Anderson, 2008).

The linea alba compliance is highest in the longitudinal direction and smallest in the transverse direction (Beer et al., 2009; Förstemann et al., 2011) which determine the great resistance offer by the LA to rectus abdominis transversal separation. Even so, the viscoelastic properties inherent to the collagen, makes the linea alba prone to increase length when the mechanical stress is prolonged in time (Hernández-Gascón et al., 2012), namely in the case of a long-lasting increased intra-abdominal pressure, such as that resulting from pregnancy (Akram & Matzen, 2014; Benjamin, van de Water, & Peiris, 2014; Boissonnault & Blaschak, 1988; Coldron, Stokes, Newham, & Cook, 2008).

The mechanical stress on linea alba is highly associated to the action of the oblique's and transversus abdominis muscles. The external oblique arises from the lower 8 ribs posteriorly to interdigitate with both the serratus and latissimus muscles. The direction of the fibers is approximately horizontal in the uppermost portion only to become oblique in the lowest portions. After contributing to the anterior portion of the rectus abdominis sheath, the remaining fibers insert onto the linea alba.

The internal oblique arises from the anterior two-thirds of the iliac crest and lateral half of the inguinal ligament to run essentially at right angles to those of the external oblique. The fibers run perpendicular to the external oblique muscle from the thoracolumbar fascia of the lower back, the anterior iliac crest and the lateral half of the inguinal ligament, to insert on the 10th to 12th ribs inferiorly and the linea alba (Fig. I - 1). The external and internal oblique muscles both have functions in the support of abdominal viscera as well as assisting in flexion and rotation of the trunk.

The transversus abdominis muscle is the innermost of the abdominal muscles, being placed immediately beneath the internal oblique muscle from the 7th to 12th costal cartilages, iliac crest, and the lateral third of the inguinal ligament. The muscle bundles run mostly horizontally, except the lower most medial fibers, which run a more inferomedial course to their insertion on the pubic crest and pubis (Kahle et al., 1991). Their extensive aponeurosis passes horizontally in the middle line of the abdomen, and is inserted into the linea alba: the upper portion lie behind the RA muscle and blend with the posterior rectus sheath while its lower part pass in front of the RA muscle (Turatti et al., 2013).

1.2 Changes in the abdominal wall morphology during pregnancy

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The functional role of the abdominal muscles during pregnancy appears to be similar to those in the non-pregnant state (Boissonnault & Blaschak, 1988) and is suggested to be important for trunk movement, pelvic stabilization, and restraint of the abdominal contents (Standring, 2008). However, the musculoskeletal morphology of the anterolateral wall of the abdomen changes as pregnancy progresses (Foti, Davids, & Bagley, 2000; Gilleard & Brown, 1996). The weight and dimensions of the uterus and its contents increases from 40 to 1000 grams, and its capacity from 4 ml in non-pregnant state to 4000 ml at term (Cunningham, Leveno, Bloom, & Spong, 2009). The maternal inferior thoracic diameter is increased (Davies, Wolfe, Mottola, & MacKinnon, 2003; Gilleard, Crosbie, & Smith, 2002) as well as the anterior and lateral dimensions of the abdomen. These changes modify the spatial relationship between the superior and the inferior abdominal muscle attachments (Cunningham et al., 2009) increasing the length of the abdominal muscles, particularly the rectus abdominis (Fast, Weiss, Ducommun, Medina, & Butler, 1990). At 38 weeks of gestation the length of the abdominal muscles increased a mean of 115% with respect to the beginning of pregnancy (Gilleard & Brown, 1996). The increment of the anterior abdominal dimensions may alter the angle of the abdominal muscle attachment in the sagittal plane (Gilleard & Brown, 1996). Alterations in the spatial relationship of muscle attachment and the muscle's angle of insertion may alter the muscles line of action and therefore their ability to produce torque (Gilleard et al., 2002; Gilleard & Brown, 1996).

1.3 Inter-rectus distance and diastasis recti abdominis

One of the muscles thought to undergo change in pregnancy is the rectus abdominis. As the fetus grows, the two muscle bellies of the rectus abdominis, connected by the linea alba, elongates and curve round as the abdominal wall expands, with most separation occurring at the umbilicus (Boissonnault & Blaschak, 1988; Fast et al., 1990; Gilleard & Brown, 1996). The augmented inter-rectus distance (IRD), often referred as *diastasis rectus abdominis* (DRA), is described as a change in the abdominal musculature, specifically in the linea alba and rectus abdominis sheath, with onset in the last trimester of pregnancy and whose peak of incidence occurs immediately after birth and the first weeks following childbirth (Boissonnault & Blaschak, 1988; Coldron et al., 2008; Dumas, Reid, Wolfe, & McGrath, 1995; Rett, Braga, Bernardes, & Andrade, 2009). Although, some studies suggested that an augmented IRD could reduce the abdominal integrity and functional strength, contributing to pelvic instability and back pain (Gilleard et al., 2002; Gilleard & Brown, 1996; Parker, Millar, & Dugan, 2009), no scientific evidence exists about the functional implications of an augmented inter-rectus distance or even about the effect of the exercise on prevention and/or reduction of IRD.

1.4 Classification and Prevalence of Diastasis Recti

Criteria and IRD cut-off value for the diagnosis of DRA vary in the literature (Akram & Matzen, 2014; Beer et al., 2009; Boissonnault & Blaschak, 1988; Bursch, 1987; Candido, Lo, & Janssen, 2005; Gilleard & Brown, 1996; Ranney, 1990; Rath et al., 1996; Spitznagle, Leong, & Van Dillen, 2007), and to date there is no international consensus on the measurement location. In a cadaver study, Rath et al (1996) defined a widening of the IRD more than 10 mm above the umbilicus, 27 mm at the level of the umbilicus and 9 mm below the umbilicus, as pathological DRA. Others defined DRA as a widening of the IRD more than 2.5 cm at one or more assessment points using digital calipers (Chiarello, Falzone, & McCaslin, 2005). In a more recent ultrasound study Beer et al (2009) suggest that in nulliparous women, the linea alba should be considered “normal” when the IRD width is less than 15 mm, at the xiphoid level, 22 mm at 3 cm above the umbilicus, and 16 mm at 2 cm below the umbilicus.

Studies have found that DRA may affect between 30% and 70% of pregnant women (Boissonnault & Blaschak, 1988), and that it may remain separated in the immediate postpartum period in 35% to 60% of women (Bursch, 1987). However the condition has also been found in 39% of older, parous women undergoing abdominal hysterectomy (Ranney, 1990) and in 52% of urogynecological menopausal patients (Spitznagle et al., 2007). Reported prevalence of DRA or increased IRD varies and may be inaccurate due to different IRD cut-off values for the diagnosis (Beer et al., 2009; Boissonnault & Blaschak, 1988; Bursch, 1987; Chiarello et al., 2005; Gilleard & Brown, 1996; Rath et al., 1996; Spitznagle et al., 2007) and use of different measurement assessment methods.

1.5 Risk factors for diastasis recti abdominis

There is scant knowledge about the risk factors for DRA. Two studies analyzed several variables such as, age, ethnicity, body mass index, height, weight gain during pregnancy, pre-pregnancy weight, gestational age at delivery, type and duration of birth (Candido et al., 2005; Rett et al., 2009). An association of DRA during pregnancy with Caucasian ethnicity and lack of regular exercise during pregnancy was suggested (Candido et al., 2005). It is considered that women with DRA have a greater number of pregnancies and deliveries (Rett et al., 2009; Spitznagle et al., 2007), and among multiparous women, it is suggested that there is a strong association between provision of childcare and DRA during pregnancy (Candido et al., 2005). However these studies were limited by the sample size, reliability of the instruments used, and were not definitive in its ability to delineate risk factors.

1.6 Procedures and instruments to assess the inter-rectus distance

The most common methods to assess IRD are palpation (Boissonnault & Blaschak, 1988; Bursch, 1987; Mantle, Haslam, & Barton, 2004; Noble, 1995) and calipers (Boxer & Jones, 1997; Hsia & Jones, 2000). However, the reported prevalence of DRA (or augmented IRD) may be inaccurate because of the lack of reliability, the low responsiveness (ability of a tool to detect small differences or small changes) and lack of validity (ability of an instrument to measure what it is supposed to measure) (Bø, Berghmans, Van Kampen, &

Morkved, 2007) in the methods and instruments used to measure the IRD. Recently, ultrasound imaging has been suggested as a useful method to assess muscular geometry and as an indirect measure of muscle activation via changes in muscle thickness during contraction (Hodges, Pengel, Herbert, & Gandevia, 2003; Rankin, Stokes, & Newham, 2006). Coldron et al. (2008) used ultrasound to characterize RA changes during the first year postpartum and Mendes (2007) et al claimed ultrasonography to be an accurate method to measure diastasis recti when compared with surgical compass during abdominoplasty. However, at the time this study was planned, search of the literature did not reveal studies addressing the intra or inter-tester reliability of the ultrasound measurement of the IRD at rest or during abdominal muscle contraction. Across-days reliability may be of interest to physiotherapists who perform repeated assessments of abdominal muscle function over time (Hides, Miokovic, Belavý, Stanton, & Richardson, 2007). Factors such as relocation of the original imaging site, reproduction of the same transducer pressure and orientation, as well as maintenance of a relatively stationary transducer position during muscle contraction, could adversely affect reliability (Hides et al., 2007) and accurate interpretation of ultrasound imaging and lead to erroneous conclusions (Klimstra, Dowling, Durkin, & MacDonald, 2007; Whittaker, Warner, & Stokes, 2009; 2010)

1.7 The effect of exercise on diastasis rectis abdominis

It has been suggested that antepartum activity level may have a protective effect on DRA and exercise may improve post-partum symptoms of DRA (Akram & Matzen, 2014). Postnatal women are encouraged to resume abdominal exercises shortly after delivery to restore their abdominal figure and fitness (Davies et al., 2003; Gilleard & Brown, 1996). To date there is scant knowledge on the most effective abdominal exercises both during pregnancy and after childbirth. In particular there is little evidence on which exercises are most effective in reduction of the rectus diastasis. The rationale behind the abdominal strengthening programs is the assumption that the contraction of all abdominal muscles will reduce the horizontal abdomen diameter in such a way that a horizontal force will be generated producing the approximation of both rectus abdominis, particularly at the umbilicus level (Liaw, Hsu, Liao, Liu, & Hsu, 2011). However, there is no evidence that this horizontal tension will produce an approximation of the rectus abdominis muscles. The horizontal force is the result of the overall action of the deep abdominal muscles (oblique’s and transversus abdominis muscles) which are anteriorly attach to the lateral side of each rectus abdominis muscles (I. A. F. Stokes, Gardner-Morse, & Henry, 2010) and posteriorly connect to the lumbar vertebral column. Thus, the horizontal tension produced by these deep abdominal muscles could pull the rectus abdominis muscle laterally toward the fixed sites on the vertebral column, increasing the inter-rectus distance (Pascoal, Dionisio, Cordeiro, & Mota, 2014).

The abdominal crunch is one of the most used exercises in abdominal strengthening programs. However, the abdominal crunch has been considered a risk exercise for development of rectus diastasis (Boissonnault & Blaschak, 1988), and lately core training with the drawing in exercise has been recommended both in the general population (Mannion, Pulkovski, Toma, & Sprott, 2008; Richardson, Hodges, & Hides, 2004; Richardson, Gwendolen, Hodges, Hides, 1999) and during pregnancy and after childbirth (Benjamin et al., 2014). It has been proposed that the activation and training of the transversus abdominis draws the bellies of the rectus abdominis muscle together (Mesquita, Machado, & Andrade, 1999; Sheppard, 1996), improves the integrity of the linea alba and increases fascial tension, allowing efficient load transference and torque production (Benjamin et al., 2014; Keeler et al., 2012). However, due to the low number and quality of the studies, there is insufficient evidence to support this statement.

2. Thesis goals and overview

The overall goal of the thesis was to describe the adaptations of the abdominal wall from pregnancy till 6 months postpartum. Therefore, the aim of the first part of the thesis (chapters II, III and IV) was to establish a reliable method for the assessment of the morphology of the abdominal wall, specifically the IRD. The purpose of the second part of the thesis (chapters V and VI) was to describe the modifications on the IRD from pregnancy till 6 month postpartum, and evaluate the muscle function during two abdominal exercises along the time.

The thesis manuscript was organized into seven chapters arranged sequentially. Between Chapter I, "*General Introduction*" and Chapter VII, "*General Discussion*", five studies are presented in papers format. Therefore, three methodological studies (chapters II, III and IV) were conducted to understand how to accurately measure IRD in women during pregnancy and postpartum period, at rest and during an abdominal muscles isometric contraction.

As ultrasound imaging is a useful instrument to evaluate muscle geometry, we decided to establish the reliability of the ultrasound measurements on IRD, compare it to palpation assessment method and measure a handheld transducer motion during two common abdominal exercises.

Hence, the test-retest reliability study "*Test-retest and Intrarater Reliability of 2D Ultrasound Measurements of Distance Between Rectus Abdominis in Women*" presented on chapter II of this thesis aimed: to evaluate test-retest and intrarater reliability of 2D ultrasound imaging of the IRD at rest and during abdominal crunch and drawing-in exercises.

In order to evaluate intra and inter-rater reliability of abdominal palpation, and to compare the results from abdominal palpation with 2D ultrasound imaging of the IRD, the study "*Reliability of the Inter-Rectus Distance Measured by Palpation. Comparison of Palpation and Ultrasound Measurements*" presented in chapter III was performed. This study allowed us to determine if the most common assessment method for IRD used in physiotherapy clinical practice could be used in research. The specific aims were: to evaluate intra and inter-rater reliability of abdominal palpation, and to compare the results from abdominal palpation with 2D ultrasound imaging of the IRD.

As the ultrasound transducer motion may interfere with accurate measurement of IRD, the study presented in chapter IV "*Ultrasound Imaging Transducer Orientation and Displacement during Static Positions of Drawing-in and Abdominal Crunch Exercise*" aimed to measure handheld transducer motion relative to pelvis, during a clinical simulation involving the two common abdominal exercises.

The purpose of the second part of the thesis (chapters V and VI) was to describe the modifications specifically on the IRD and the prevalence of rectus diastasis from pregnancy till 6 month postpartum, and evaluate the muscle function during two abdominal exercises along the time.

Chapter V presents the longitudinal study "*Prevalence and risk factors of Diastasis Recti Abdominis from late pregnancy to 6 months postpartum, and relationship with lumbo-pelvic pain*". This study describes the prevalence of DRA at gestational week 35, and 6-8, 12-14, and 24-26 weeks postpartum; the possible risk factors related to the presence of DRA at 6 months postpartum and whether women with DRA at 6 months postpartum have more lumbopelvic pain than women without DRA.

Finally in chapter VI the longitudinal study "*Inter-recti Distance at Rest, During Abdominal Crunch and Drawing in Exercises during Pregnancy and Postpartum*" which compared the IRD measured in women at gestational week 35-41 and at three moments during postpartum: 6-8, 12-14, 24-26 weeks, in two conditions: at rest and during two commonly prescribed abdominal strengthening exercises.

3. Methodological considerations

Although the materials and methods used to perform the studies included in this thesis are described with detail in each of the studies (chapters II to VI) here is a brief overview of the global procedures.

3.1 Ultrasound measurements

Measurements of the inter-rectus distance were made in ultrasound images in brightness mode (B-mode) recorded by mean of an ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer and a fixed frequency of 12 MHz. The ultrasound protocol and ultrasound image interpretation were previously discussed and practiced with an experienced radiologist. The same investigator (Mota, P.) did all examinations and was blinded to the subjects' identification and to the values of the IRD measurements in all studies.

Images were exported in Digital Imaging and Communications in Medicine (DICOM) format and processed offline using a customized Matlab environment (Matlab, Image Processing Toolbox, Mathworks). To calculate the IRD, each US image was assumed as a pixel based coordinate system with origin on the left superior corner of the image Using *ginput* Matlab function the visible contour of both left and right RA was digitized by an examiner as pixels coordinates, i.e. column (x) and row (y).

$$x = b_1 y^4 + b_2 y^3 + b_3 y^2 + b_4 y + b_5 \quad (1)$$

An algorithm was used to suggest a possible location of the medial end-point of RA muscles. The first step was to interpolate the point marked by the observer and fit them to a curve. We assumed a parabola-like-curve which equation (1) defines the correspondent shape. In this equation, the x and y values of the marked points was used as an input to determine the coefficient of the polynomial. Although we used a fourth order polynomial, we also tested the fit using third and second order polynomial and found that the fourth order polynomial had a better fit. In the second step, we computed the interpolated coordinates. From our observation, the start and end-point of the linea-alba was the point of inflexion of the interpolated curves (Fig. I-2A. Red dots and yellow line). So we determined the discrete derivative of the interpolated x-coordinate and the point at which the sign changed was considered as the point of inflexion. The determined inflexion point was then presented to the user, to make the selection of the end points of the linea-alba easier (Fig. I-2B).

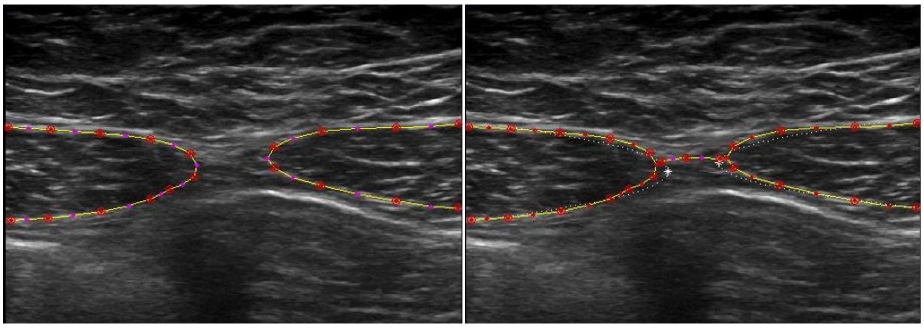

Fig. I-2 A. Rectus abdominis (both) ultrasound image. B. Points digitalized by the examiner on the muscles contour (red dots). Interpolated points are using an algorithm according to a parabola-shape like curve (white points); parabola inflection point (white asterisk) suggesting the end-points for IRD measurement on the medial margin of both rectus abdominis.

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3.2 Procedure for transducer motion analysis

Motion capture was collected with a thirteen camera Qualisys system (model: Oqus-300plus) operating at a frequency rate of 50Hz. The capture volume provided by the cameras enabled a mean camera residual below 0.5mm.

The transducer motion was tracked by means of a customized cluster composed by 4 non-collinear reflective markers fixed to the long axis of the transducer and by 2 additional markers virtually built at the lower extremity of the transducer using a digitizing pointer.

Fig. I-3. Ultrasound transducer with a customized cluster composed by 4 non-collinear reflective markers fixed to the long axis of the transducer.

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Pelvis position was tracked by means of 4 reflective markers applied to both anterior-superior iliac spines and iliac crests.

The Visual 3D software (Visual 3D Basic RT, C-Motion, Inc., Germantown, MD) was used for tridimensional reconstruction of the pelvis and the ultrasonography transducer in the resting position (static calibration). The tridimensional reconstruction of the model enabled us the quantification of the position and rotation of the transducer relative to the pelvis segment. Two local reference coordinate systems were defined: the pelvis reference coordinate system origin was in the midpoint between the right and left anterior iliac spines and the transducer reference system origin was located at the midpoint of the two virtual markers on the base of the transducer (Fig. I-4).

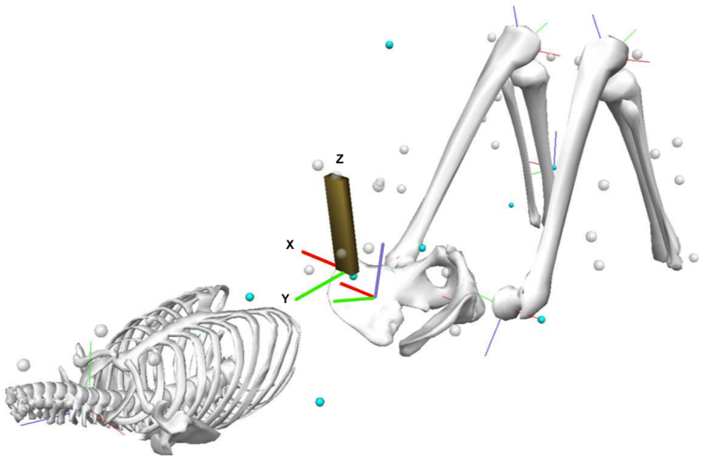

Fig. I-4. Two local reference coordinate systems were: 1) the pelvis reference coordinate system, which origin was in the midpoint between the right and left anterior iliac spines; 2) transducer reference system which origin was located at the midpoint of the two virtual markers on the base of the transducer.

We have quantified the orientation of the transducer relative to the pelvis around the X-axis (cranial/caudal tilt of the transducer), Y-axis (medial/lateral tilt of the transducer) and Z-axis (clockwise/counterclockwise rotation of the transducer). The translational movement of the transducer along the YZ plane was calculated through the scalar distance of the midpoint between the two proximal markers placed in the transducer and the midpoint between the right and left anterior-superior iliac spines. The position of the transducer relative to the pelvis during the calibration of the subject (static motion capture) was assumed as zero degrees in all the axes of rotation and zero meters of translation regarding the linear position of the transducer.

4. Participants

Altogether, 187 women participated in this thesis (Fig. I-5). Twenty-four (12 women in the postpartum period and 12 women with different parity (0-2 children)) and twenty (10 women in the postpartum period and 10 women with different parity (0-2 children)) healthy female volunteers were included in the test-retest study presented on chapter 2 and 3 respectively. Another twenty female volunteers (10 women in the postpartum period and 10 nulliparous women) participated in the exploratory study for the transducer motion.

In addition, one hundred and twenty-three first time pregnant women participated in the longitudinal observational studies. The participants were eligible for the study if they were first time pregnant, agreed to participate in four testing sessions (one during pregnancy at gestational week 35-41, and three in postpartum) and were able to perform the two different abdominal exercises. Exclusion criteria in the longitudinal studies were any kind of conditions affecting the ability to perform activities of daily living or any symptoms that required medical attention e.g., high-risk pregnancies, stillbirth or delivery before gestational week 37, previous spinal or abdominal surgery and neuromuscular diseases. Women were also excluded if one of the testing sessions was missed.

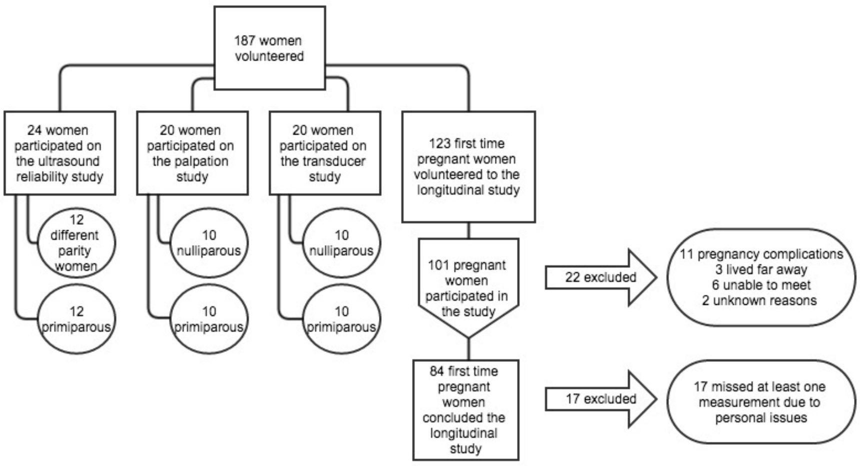

Fig. I-5. Flowchart of the participants in this study.

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5. Ethics

The study was approved by the Review Board of the University of Lisbon, Faculty of Human Kinetics (appendix). Written informed consent was obtained before participation and the rights of the participants were protected and were provided in verbal and written form following the Helsinki declaration (Helsinki, 1982).

Chapter II

Test-retest and Intrarater Reliability of 2D Ultrasound Measurements of Distance Between Rectus Abdominis in Women

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Abstract

Study design: Single-group test-retest reliability study.

Objectives: To evaluate test-retest intra-observer reliability of 2D ultrasound measurement of the distance between rectus abdominis, the inter-rectus distance (IRD).

Background: Diastasis recti is defined as the separation of the two rectus abdominis muscles with a reported prevalence of between 30% and 70% in women during pregnancy and in the postpartum period. The condition is difficult to measure, and ultrasound imaging has been suggested as a useful method to quantify the diastasis. However, to date no studies have investigated intra or inter-tester reliability of ultrasound to measure distance between rectus abdominis during rest and contraction.

Methods: Ultrasound images from the rectus abdominis were recorded on 24 healthy female volunteers at rest and on two conditions of abdominal contraction: Abdominal Crunch and Drawing-In exercises. The probe was positioned in two locations: below and above the umbilicus. A blinded investigator measured the IRD offline from two different ultrasound images collected on two different days (test-retest). Additionally, re-analyses of the same ultrasound images were done on two separate occasions (intra-image).

Results: Test-retest measurements of IRD demonstrated good to very good reliability with ICC values between 0.74 and 0.90. The only exception was for IRD measured 2 cm below the umbilicus on the abdominal crunch exercise, with an ICC of 0.50. For intra-tester reliability of the same images, the ICC values were all above 0.90.

Conclusion: Ultrasound imaging is a reliable method for measuring the inter rectus distance at rest and during Abdominal crunch and Drawing- in exercises.

Keywords

Diastasis, Postpartum, Reliability, Ultrasonography.

1. Introduction

Diastasis recti abdominis (DRA) has been defined as an impairment characterized by a midline separation of the two rectus abdominis (RA) muscles along the linea alba (LA).[27,22] This increased inter rectus distance (IRD) has its onset during pregnancy and/or immediately after birth and the first weeks following childbirth.[5,12]

As the fetus grows the two muscle bellies of the RA connected by the LA, elongate and curve as the abdominal wall expands, and separation of the two muscle bellies with protrusion of the umbilicus may occur.[5,14,13] Studies have found that diastasis recti may affect between 30% and 70% of pregnant women[5], and that it may remain separated in the immediate postpartum period in 34.9%[9] to 60% of women[7,5,6]. However the condition has also been found in 38.7% of older, parous women undergoing abdominal hysterectomy[25] and in 52% of urogynecological menopausal patients.[27]

Reported prevalence of diastasis recti or increased IRD may be inaccurate because of unreliable methods to measure the condition with the most common assessment method being palpation[5,7,22,19], and calipers[6,16]. Ultrasound imaging has recently been suggested as an useful method to assess muscular geometry and as an indirect measure of muscle activation via changes in muscle thickness.[24] Coldron et al[10] used ultrasound to characterize RA changes during the first year postpartum and Mendes[20] et al claimed ultrasonography to be an accurate method to measure diastasis recti above and at the umbilicus when compared with surgical compass during abdominoplasty. However, search of the literature did not reveal studies addressing the intra or inter-tester reliability of the ultrasound measurement of the IRD at rest or during abdominal muscle contraction. Across-days reliability may be of interest to physiotherapists who perform repeated assessments of abdominal muscle function over time[15] and factors such as relocation of the original imaging site, reproduction of the same transducer pressure and orientation, as well as maintenance of these factors during muscle contraction could adversely affect reliability.[15]

The aims of the present study were to evaluate test-retest and intrarater reliability of 2D ultrasound imaging of the IRD at rest and during abdominal crunch and drawing-in exercises, and to verify the differences on IRD related to the postpartum condition.

2. Methods

2.1 Design

This was a test–retest study evaluating the intrarater reliability of IRD measurements. For the test-retest analysis two test sessions were performed. In addition, the images collected during session 1 were analyzed a second time by the same investigator.

2.2 Participants

Twenty-four healthy female volunteers participated in this study. Twelve of the women were in the postpartum period and were recruited from a private physiotherapy clinic and the others among colleagues, friends and family. Demographic data with respect to age, body mass index (BMI) and parity are presented in *Table II-1*. The participants were eligible for the study if they agreed to participate in two testing sessions and were able to perform two different abdominal exercises. To ensure external validity, 12 women in postpartum period (less then 6 months) and 12 women with different parity (range 0 to 2 births), were included in the study. Pregnant women were excluded from the present study.

The study was approved by the Review Board of the Technical University of Lisbon, Faculty of Human Kinetics. Signed informed consent was obtained before participation in this study and the rights of the participants were provided in verbal and written form.

2.3 Instrumentation and procedures

An ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer was used to collect images in brightness mode (B-mode) by the same examiner. The investigator was a physiotherapist with specific training in image capturing and measuring IRD. Before starting the study, the ultrasound protocol and analysis were discussed and practiced with an experienced radiologist.

The transducer was placed transversely along the midline of the abdomen in two locations with the center of the umbilicus as a reference: 2 cm above the umbilicus and 2 cm below the umbilicus. Initially, each measurement location was marked on the skin in order to standardize the position of the transducer. Ink marks were drawn with the subject in supine resting position with the knees bent at 90º and feet resting on the plinth, arms alongside the body *(Figure II-1)*.

During image acquisition the bottom edge of the transducer was positioned to coincide with the correspondent skin marker and moved laterally until the medial borders of both RA muscles were visualized. The orientation of the transducer was then adjusted to optimize visualization of the image. Images were collected immediately at the end of exhalation, as determined by visual inspection of the abdomen following the recommendations of Teyhen et al.[29] Additionally particular attention was paid to the pressure imposed on the probe in order to avoid reflexive response from the participants.

Still images were obtained with subjects in the supine resting position (knees bent at 90º and feet resting on the plinth, arms alongside the body) and on two abdominal contraction conditions: abdominal crunch *(Figure II-2)* and drawing-in exercise *(Figure II-1)*. One image was taken at each location under each condition. The abdominal crunch exercise was started from the resting position and the subjects were instructed to raise the head and shoulders upwards until the shoulder blades cleared the table. Subjects held this position until told to return to the starting position. The drawing-in exercise also started from the resting position, and the subjects were instructed to inhale and after exhaling draw in the abdominal musculature towards their spine. Before starting the procedure the subjects were verbally instructed about correct performance of the two exercises. The verbal instructions are provided in *Table II-2*. During the Drawing-In maneuver activation of the transversus abdominis muscle was confirmed by placing the transducer laterally between the iliac crest and rib cage.[28] Every contraction was held for three seconds for data collection with a resting time of 6 to 10 seconds between each repetition. After the test a convenient day for retest was scheduled with the participants.

The set of 12 images per subject from each of the 3 conditions (rest, abdominal crunch and drawing-in) from both locations (2 cm above and below the umbilicus) in the 2 days were exported in JPG format for further offline processing. Reliability was analyzed on IRD measurements during session 1 (intra-image reliability) and between sessions (test-retest reliability). The investigator was blinded to the subjects ID and to the values of the IRD measurements.

2.4 Inter-rectus distance (IRD) measurement

Analyses of 2D ultrasound distances were conducted offline by the same investigator, using a customized code made on specific software (Matlab, Image Processing Toolbox, Mathworks Matlab, USA). Ultrasound images were assumed as a pixel based coordinate system, with the origin in the top left hand corner of the image. In this system an '*x'* and *'y'* coordinate could be used to locate a point in the image and distance between two or more point could be calculated. On ultrasound images the IRD is characterized by the transverse linear distance from the medial border of the rectus abdominis of one side to the corresponding position of its counterpart on the other side. Using this procedure, two points corresponding to the medial muscular insertions sites of both rectus abdominis on the linea alba, must be identified on the ultrasound images. From our observations these points are close to the inflection point of a parabola-like-curve that could be assumed for the ultrasound image of each rectus abdominis muscle contour *Figure II-3* (red dots and yellow line). In order to improve the accuracy of the identification of these two points, an algorithm was developed and implemented using a customized Matlab code. Thus, the first step in the algorithm was to interpolate a set of 8-10 points manually digitalized by the examiner on the visible contour of both muscle bellies, and fit them to a parabola-like-curve. Using the coordinates of those digitized points a fourth order polynomial equation was fitted in order to determine the coefficient of the polynomial and the inflexion point of the interpolated curve. The discrete derivative of the interpolated *x*-coordinate and the point at which the sign changed was considered as the parabola point of inflexion *Figure II-4* (white asterisks). The determined inflection point and the interpolated parabola-like-curve were overlapped on the original ultrasound image, to guide the examiner on the identification of the medial margins of the RA and improve the accuracy of IRD measurements. Besides the software suggestion, the examiner has the final decision about the location of the medial margins of the RA muscles used on IRD measurements.

2.5 Statistical Analyses

The intra-class correlation coefficient (ICC) for one way random effect model was used to assess the level of consistency across the 2 IRD measurements made on two different ultrasound images and collected on two different days (test-retest), and across the 2 IRD measurements made on the same ultrasound image (intra-image).

The scale from Altman[1] was used in the classification of the reliability values. ICC values less than or equal to 0.20 were considered poor, 0.21 to 0.40 fair, 0.41 to 0.60 moderate, 0.61 to 0.80 good and 0.81 to 1 very good.

Standard error of measurement (SEM) was used to examine the precision of measurement and it was calculated according to SEM = pooled Standard Deviation*$\sqrt{1-ICC}$. To represent a difference in IRD beyond measurement error, the minimum detectable change (MDC) was calculated as 1.96 * SEM *$\sqrt{2}$ [23]. These analyses were performed for each of the outcome variables: IRD at rest condition, abdominal crunch and drawing in exercise, 2 cm above and 2 cm below the umbilicus.

The Bland-Altman plot of difference against the mean was also used to compare the limits of agreement and mean bias between plots.[4] The Standard Deviation (SD) of the differences between test and retest was calculated, and then multiplied by 1.96 to obtain the 95% random error component.[2]

In order to verify the differences on IRD related to the postpartum condition, the 12 postpartum women were compared to the women with different parity using an independent t-test.

All statistical analyses were made using specific software (IBM-SPSS, Version 19) and a critical level of $p < 0.05$ was considered statistically significant.

3. Results

All participants returned for the second test after a mean of 3.9 days (SD = 3.9, range 1 to 16 days) and all reported that they complied with the request not to practice any of the exercises between tests. There were no dropouts. The IRD values for each measurement are shown in Table II-3. No significant differences were found in the IRD between women in postpartum and the other women with different parity (Table II-4). In general, the smallest IRD values were from abdominal crunch exercise, and the biggest were from the drawing-in exercise.

3.1 Intra-tester reliability of the ultrasound analyses (intra-image)

The ICC values for the IRD measured on the same image at two different occasions revealed very good reliability for every condition tested (Table II-5). The Rest condition demonstrated less variability than the measurements conducted during Abdominal Crunch and Drawing-In, but the ICC values were all above 0.90. The precision of repeated measurements of the same images was higher (revealed by lower SEMs) compared with recaptured images. The MDC values ranged from 1.80 to 5.52 mm. The Bland-Altman plot (Figure II-5) showed that the mean of differences of IRD on test-retest was closer to zero (0.052) mm, and the limits of agreement were narrower compared with the values found on different images (-1.95 mm and 2.05 mm).

3.2 Test-retest across days (inter-image)

The ICC values for the IRD during the rest condition demonstrated good reliability for 2 cm below the umbilicus with an ICC (95% CI) of 0.78 (0.56-0.90), and very good reliability for 2 cm above the umbilicus with an ICC (95% CI) of 0.87 (0.73-0.94), (Table 6). The inter rectus distance for the rest condition demonstrated higher ICC values than the measurements from the abdominal crunch, which showed very good reliability above the umbilicus with an ICC (95% CI) of 0.83 (0.65-0.92), but moderate reliability below the umbilicus with an ICC (95% CI) of 0.50 (0.14-0.75). For the drawing-in, ICC was very good 2 cm above umbilicus with an ICC (95% CI) of 0.90 (0.79-0.96), and good 2 cm below the umbilicus with an ICC (95% CI) of 0.74 (0.48-0.88) (Table 6). SEM values were very similar across all conditions, but 2 cm below the umbilicus during drawing-in and abdominal crunch they showed higher variability with values of 3.15 mm and 4.36 mm respectively. The MDC values ranged from 6.32 to 12.08 mm. The Bland-Altman plot showed that the mean of differences of IRD on test-retest was - 0.33 mm and the limits of agreement were between -8.67 mm and 8.34 mm (Figure II-6).

4. Discussion

The present study demonstrated very good reliability for the intra-tester measurements in the same image for all the conditions tested, with ICC values above 0.90, low values of SEM (range 0.65 to 1.99) and MDC (range 1.80 to 4.29). These results are in line with the values found by Liaw et al.[18] The test-retest measurements across days showed good reliability during rest and drawing-in exercises below the umbilicus with ICC values of 0.78 and 0.74 respectively and very good reliability during rest, abdominal crunch and drawing-in exercises above the umbilicus with ICC values of 0.87, 0.83 and 0.90 respectively. The lowest ICC value of 0.50 was found below the umbilicus and during contraction, with moderate reliability for abdominal crunch. The higher values found on the SEM (range 2.28 to 4.36 mm) and on the MDC (range 6.32 to 12.08 mm) revealed lower precision of the IRD measurements.

The lower values found below the umbilicus may be explained by the influence of the amount of subcutaneous fat[18] in this location. This could have interfered with the determination of where to mark the skin, positioning of the probe and the ability to maintain a constant pressure during image acquisition. During the abdominal crunch exercise the participants had to move the upper body and this may have induced movements under the transducer. Nevertheless the ICC was moderate to good.

In general, there are several potential sources of measurement errors: the subjects, the testing, the scoring, the instrumentation and factors such as the instructions from the examiner, participant motivation, and the participants skill and motor control may affect performance in different days.[17] To mitigate against some of these potential sources of errors the position of the subject, examiner's instructions, the transducer location and its inclination, the pressure applied to the transducer on the abdominal wall, and the room temperature were standardized.

Criteria for the diagnosis of DRA vary in the literature.[5, 7, 14, 26, 27, 25, 8, 3] Beer et al[3] suggest that in nulliparous women, the LA could be considered "normal" when the width is less than 1.5 cm at the xiphoid level, 2.2 cm at 3 cm above the umbilicus, and 0.6 cm at 2 cm below the umbilicus. In our study we found higher mean values for IRD at 2 cm below the umbilicus in 12 subjects. An explanation for this difference is that we also included parous women who are expected to have wider or greater IRD.[14, 10,5 ,19] However, no significant differences were found in the IRD between women in postpartum and the other women with different parity.

In studies of postpartum women, DRA has been defined as the LA having a width greater than 2-finger breadth (1.5 cm) when measured with palpation,[5, 14, 27] or 2 cm when measured with a dial caliper at or above the umbilicus during a partial sit-up.[18] However the inaccuracy and possible low reliability of the measurement tools used are possible limitations of previous studies.

Computed tomography (CT) and magnetic resonance imaging (MRI) are currently considered the methods of choice to examine the abdominal wall, but they are expensive and CT exposes the patient to radiation[20], making it impossible to use in pregnant women. Hence, ultrasonography has been proposed as a non-invasive technique that can be repeated several times[20] during pregnancy.

The current investigation examined many aspects of reliability of the ultrasound measurements. The two RA muscles were identified in both relaxed and contracted conditions. Furthermore, repeated measurements were conducted from the same stored images as well as across images collected and measured on two different days. It would be expected that measuring the IRD repeatedly, even on different days from stored images, would be associated with higher values of ICC. This is because measuring the distance between two well defined muscles in the ultrasound images is a relatively straight forward task. Our results from the IRD and the results of Hides et al[15], about the thickness of the internal oblique and transversus abdominis muscles, support this premise, with both studies reporting very high values of ICC from repeated measures of the same image. However, accurately re-imaging the subject to obtain comparable images may require a higher level of skill. On the current study the measurements from recaptured images showed from good to very good reliability, with the only exception of moderate reliability in the abdominal crunch exercise. The lower precision shown by higher SEM and MDC values and the wide 95% limits of agreement confirm the inferior reliability of recaptured images compared to repeated measurements of the same stored image.

Interestingly, during the drawing-in exercise the IRD values demonstrated a greater separation than during rest or abdominal crunch (Table II-3). This requires further study as this exercise is considered to be gentler than abdominal crunch and commonly recommended for low back pain both during pregnancy and after childbirth. However, to date there are no randomized controlled trials on the effect of different abdominal exercise to treat DRA in the peripartum period. A follow-up study on the IRD in pregnancy and postpartum in different muscle contraction conditions is being conducted.

The current study is unique in the reliability tests on the IRD measurements and the use of different locations and contraction conditions to better objectively quantify the separation between the two rectus abdominis muscles. A strength of this study is the blinding of the observer to all the results of IRD measurements until the end of the process. To ensure external validity, 12 subjects in postpartum period and 12 women with different parity, were included in the study. In general the IRD was greater in postpartum women, but no significant differences were found in the IRD between the two groups. Consistent with our findings, Liaw et al[18] also noted that the medial margins of the RA appear to be indistinct where the fascial borders become less clear in postpartum women. We used a customized Matlab code to implement a method of ultrasound images segmentation based on explicit shape representation defined by a known point distribution model.[11] In fact, a semi-automated ultrasound image segmentation method was used in order to help the examiner to identify the medial margins of both RA muscles and improve the accuracy of IRD measurement. However the examiner has always the final decision. We believe that in the near future this Matlab code could be implemented in the software embedded in the ultrasound scanners, helping clinicians to accurately measure the IRD or other muscular morphometric parameters (e.g. muscle cross sectional area).

The limitations of this study include the use of only one rater with limited experience in ultrasound imaging and inclusion of only healthy subjects with no musculoskeletal or neurological symptoms. It may be more difficult to reliably measure subjects with symptoms that can interfere in the performance of the exercises across the days or in the last gestational weeks where wider IRD may require a broader view of the abdominal wall to be able to see both RA muscles on the same image. Because the main goal of this study was to evaluate test-retest and intrarater reliability of the IRD in different contraction conditions, we excluded pregnant women from this study, because the IRD is constantly changing with the progress of pregnancy and movement/position of the baby.[21] This may influence the reliability of the test-retest. Only intra-rater test-retest reliability of IRD measurements with ultrasound imaging was studied. Data on inter-rater reliability is needed especially for longitudinal studies including more than one investigator.

5. Conclusion

The 2D ultrasound imaging proved to be a reliable method to measure IRD in women. We suggest the use of ultrasound imaging in future studies to reliably measure the changes in the IRD during rest, abdominal crunch and drawing-in exercises.

Table II-1. Background Variables.

Variables	All subjects N=24	Post-partum N=12	Women different parity N=12
Age *(years)*	30.54 *(range 16-55)*	31.17 *(range 26-36)*	29.92 *(range 16-55)*
Body Mass Index *(kg/m^2)*	22.71 *(range 18.90-28.51)*	23.96 *(range 20.76-28.51)*	21.46 *(range 18.90-24.61)*
Parity	0.75 (range 0-2)	1	0.5 (range 0-2)
Length of time since last pregnancy		10.91 weeks *(range 9-13)*	11.5 years *(range 1-24)*
College/University education	20/24	12/12	8/12

** Values are mean (range), except for college/university education.*

Table II-2. Verbal instructions.

Rest/Start Position	Flex your knees; keep your feet on the plinth. With your hands push your knees up to your chest and then let them go down until your feet reach the plinth again. Arms along your body and breath normally.
Abdominal Crunch	Inhale and exhale. Lift your head and slide your hands along the front of your thighs to touch your knees with the fingertips, until you feel your shoulder blades off the table. Hold there for three seconds.
Drawing-In	Inhale and exhale. Pull your belly button in and back towards the spine. Do not move your pelvis. Hold there for three seconds.

Table II-3. Inter Rectus Distance measures during Rest, Abdominal Crunch and Drawing-In exercises. * N=24

Condition	Probe location	IRD Test 1A	IRD Test 1B	IRD Test 2
Rest	2 cm Above	17.44 (7.34)	17.51 (7.51)	18.93 (7.88)
	2 cm Below	8.01 (4.82)	7.54 (4.98)	8.35 (4.80)
Abdominal Crunch	2 cm Above	16.99 (6.75)	17.01 (6.03)	18.45 (6.07)
	2 cm Below	9.22 (6.66)	9.37 (6.81)	7.93 (5.49)
Drawing-In	2 cm Above	19.38 (7.57)	19.11 (7.62)	19.51 (7.58)
	2 cm Below	9.91 (6.54)	9.90 (6.61)	9.44 (5.87)

** Values represent mean in mm (standard deviation) for each dependent measure based on state (Rest, Abdominal Crunch and Drawing-In) and site (2 cm above or below the umbilicus). Test 1 and 1B represent the measurements made on different days on the same stored image. Test 2 represent the measurements made on a different image collected across days.*

Table II-4. Inter Rectus Distance measures during Rest, Abdominal Crunch and Drawing-In exercises * for the women in post-partum and women with different parity, and Independent t-test values.

Condition	Probe location	PP (N=12)	DP (N=12)	Mean diff (95%CI)	t-test#
Rest	2 cm Above	18.26 (7.59)	16.62 (7.31)	-1.64 (-7.95-4.67)	0.595
	2 cm Below	8.87 (4.92)	7.15 (4.77)	-1.72 (-5.82-2.38)	0.394
Abdominal Crunch	2 cm Above	19.55 (7.00)	14.44 (5.64)	-5.12 (-10.50-0.27)	0.061
	2 cm Below	7.49 (5.33)	10.93 (7.60)	3.45 (-2.12-9.01)	0.212
Drawing-In	2 cm Above	22.32 (8.05)	16.43 (6.01)	-5.89 (-11.90-0.12)	0.055
	2 cm Below	11.16 (7.50)	8.87 (5.46)	-2.49 (-8.05-3.06)	0.363

Abbreviations: PP= Post Partum women; DP= Different Parity women; Mean diff= Mean difference between groups and confidence intervals.

** Values represent mean (standard deviation) in mm for each dependent measure based on state (Rest, Abdominal Crunch and Drawing-In) and site (2cm above or below the umbilicus) during test 1.*

 # Significant difference in IRD between groups ($P<0.05$)

Table II-5. Intra-rater reliability across repeated measurement of the same image.

Condition	Probe location	$ICC_{1,1}$ (95%CI) Intra-image	SEM (mm)	MDC_{95} (mm)
Rest	2 cm Above	0.98 (0.95-1.00)	1.04	2.88
	2 cm Below	0.96 (0.90-0.98)	0.97	2.69
Abdominal Crunch	2 cm Above	0.94 (0.88-0.98)	1.55	4.29
	2 cm Below	0.97 (0.93-1.00)	1.15	3.20
Drawing-In	2 cm Above	0.93 (0.85-0.97)	1.99	5.52
	2 cm Below	0.99 (0.97-1.00)	0.65	1.80

Abbreviations: $ICC_{1,1}$= Intra Class Correlation one way random effect model (95% confidence interval); SEM= Standard Error of Measurement; MDC_{95}= Minimum Detectable Change at the 95% confidence level.

Table II-6. Intra-rater reliability across 2 days.

Condition	Probe location	$ICC_{1,1}$ (95%CI) Inter-image	SEM (mm)	MDC_{95} (mm)
Rest	2 cm Above	0.87 (0.73-0.94)	2.75	7.63
	2 cm Below	0.78 (0.56-0.90)	2.28	6.32
Abdominal Crunch	2 cm Above	0.83 (0.65-0.92)	2.48	6.89
	2 cm Below	0.50 (0.14-0.75)	4.36	12.08
Drawing-In	2 cm Above	0.90 (0.79-0.96)	2.38	6.59
	2 cm Below	0.74 (0.48-0.88)	3.15	8.74

Abbreviations: $ICC_{1,1}$= Intra Class Correlation one way random effect model (95% confidence interval); SEM= Standard Error of Measurement; MDC_{95}= Minimum Detectable Change at the 95% confidence level.

Fig. II-1. Rest position, start and end position of drawing-in exercise.

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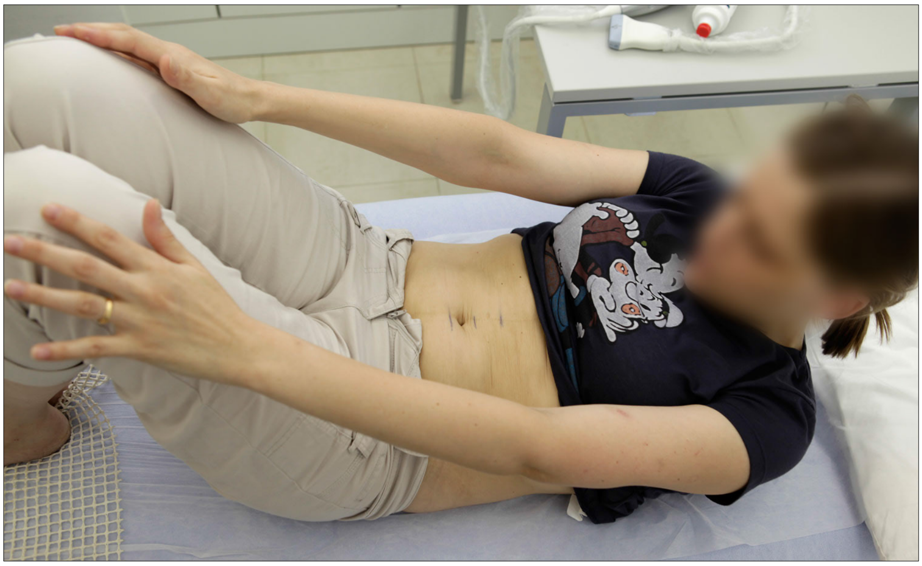

Fig. II-2. Abdominal crunch exercise.

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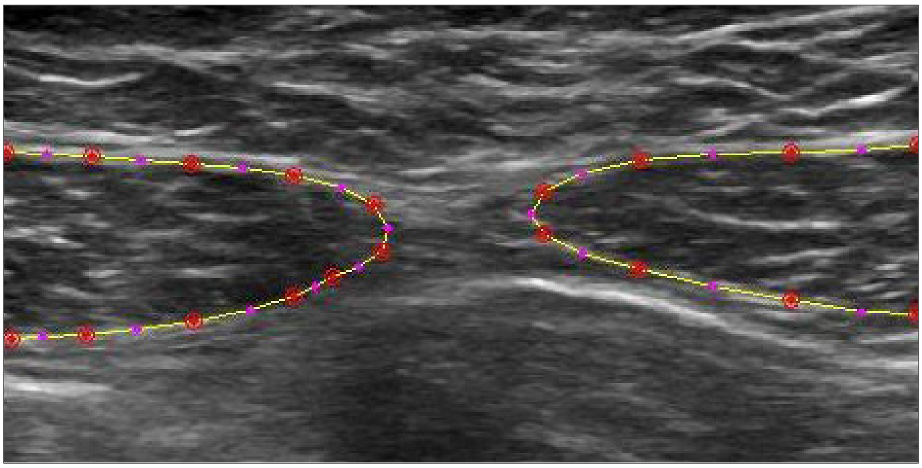

Fig. II-3. Rectus abdominis ultrasound image. Points digitalized by the examiner on the muscles contour (red dots).

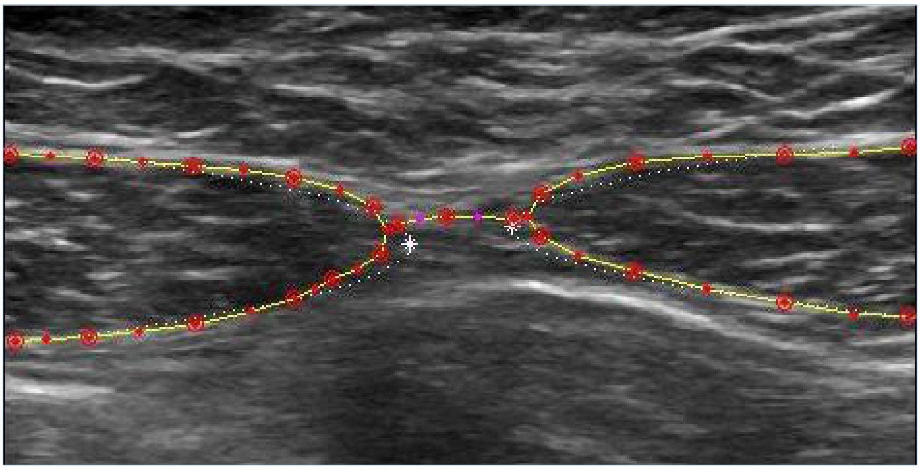

Fig. II-4. Rectus abdominis ultrasound image. Interpolated points using an algorithm according to a parabola-shape like curve (white points); parabola inflection point (white asterisk) suggesting the end-points for IRD measurement on the medial margin of both RA.

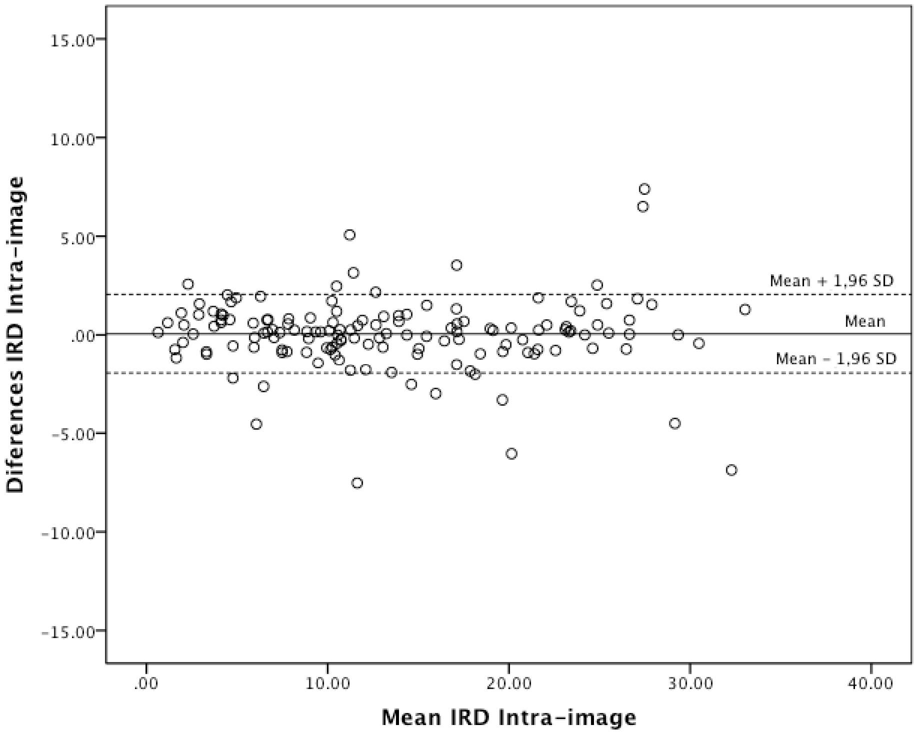

Fig. II-5. Plot of difference against mean (in mm) for measurements of the same stored images, with mean difference and 95% limits of agreement indicated.

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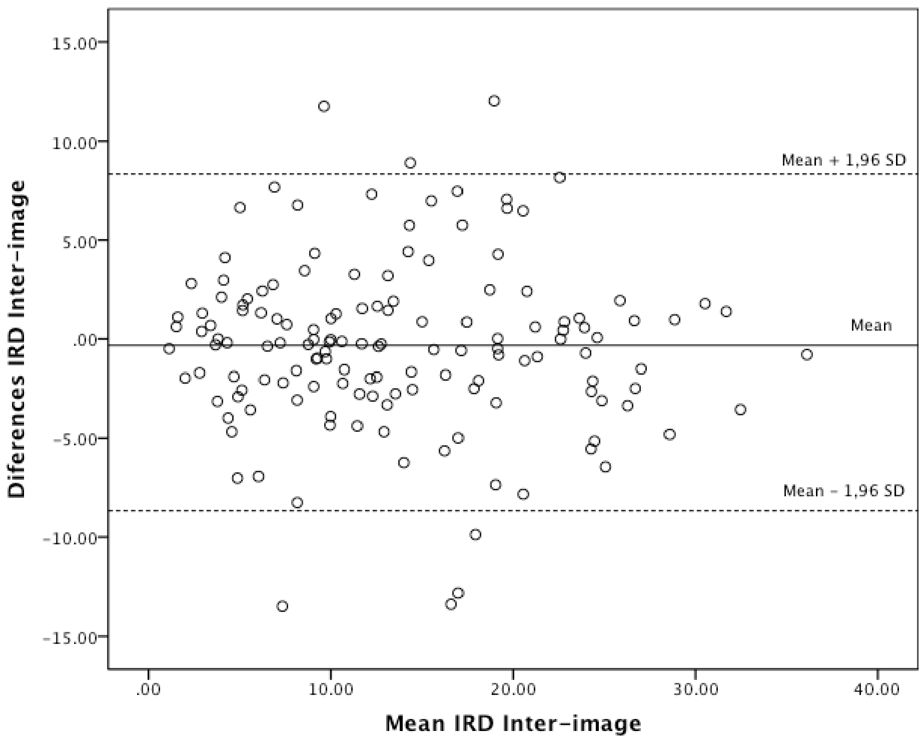

Fig. II-6. Plot of difference against mean (in mm) for the recaptured images, with mean difference and 95% limits of agreement indicated.

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Chapter III

Reliability of the Inter-Rectus Distance Measured by Palpation. Comparison of Palpation and Ultrasound Measurements

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Abstract

An increased inter-rectus distance (IRD) is a common condition in late pregnancy and in the postnatal period. The condition is difficult to assess. Palpation is the most commonly used method to assess IRD. To date there is scant knowledge of intra and inter-tester reliability of palpation to measure IRD and how palpation compares with ultrasound measurements.

The aims of this study were: 1) evaluate intra and inter-rater reliability of abdominal palpation; 2) validate abdominal palpation of IRD measurements using ultrasound imaging as a reference.

Two physiotherapists (PTs) conducted the palpation study in random order, blinded to each other's assessments. IRD was measured as finger widths between the two rectus abdominis (RA) muscles. Ultrasound images were recorded at the same locations as the palpation test. A blinded investigator measured the IRD offline.

Palpation showed good intra-rater reliability between days expressed by a weighted Kappa (wK) higher than 0.7 for both physiotherapists, and moderate inter-rater reliability (wK=0.534). Ultrasound was found to be more responsive for differences in IRD compared with values obtained by palpation.

The intra-rater reliability was higher than the inter-rater reliability. Besides the difference in experience with palpation testing between the PTs, this result may be due to differences in finger width and/or the subjective interpretation of abdominal soft-tissues pressure. Ultrasound measures are highly sensitive to changes of IRD, which is not possible to replicate by palpation assessment using a finger width scale.

Palpation has sufficient reliability to be used in clinical practice. However, ultrasound is a more accurate and valid method and is recommended in future research of IRD.

Keywords:

Diastasis, Reliability, Palpation, Ultrasonography.

1. Introduction

The lateral-anterior abdominal wall consists of five paired muscles with fibers oriented vertically, horizontally and obliquely. These muscles have skeletal attachments on the thoracic cage and pelvis and also on the spinal column via the thoracolumbar fascia. The right and left sides of the abdominal wall are connected via the Linea Alba aponeurose.

During pregnancy the Linea Alba reduces c bellies of the rectus abdominis (RA) curve round the abdominal wall, increasing the midline separation of the two RA muscles along the Linea Alba (Boissonnault & Blaschak 1988; Fast et al. 1990; Gilleard & Brown 1996). This gap, the Inter Rectus Distance (IRD) is often referred as *diastasis recti abdominis* (DRA) (Noble 1995; Spitznagle et al. 2007; Coldron et al. 2008). Studies have found that an increased DRA may affect between 30% and 70% of women during pregnancy (Boissonnault & Blaschak 1988), and that it may remain separated in the immediate postpartum in 34.9% (Boissonnault & Blaschak 1988) to 60% of women (Bursch 1987; Boissonnault & Blaschak 1988; Boxer & Jones 1997). Knowledge of changes in RA postpartum is important for the development of effective postnatal exercise programmes and general postnatal advice (Coldron et al. 2008).

In physiotherapy the most commonly used assessment methods to evaluate IRD are palpation (Bursch 1987; Boissonnault & Blaschak 1988; Noble 1995; Mantle et al. 2004) and calipers (Boxer & Jones 1997; Hsia & Jones 2000). However, the reliability of these methods is unclear. Newer methods are available to access muscle and connective tissues morphometric parameters, such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and Ultrasound Imaging. Recently, Mota et al. (2012) found ultrasound imaging to be a reliable method for measuring IRD. Nevertheless, in clinical practice, palpation may still be the most commonly used method, as it is easy to apply, does not require special equipment and has a low financial cost. Accurate and reliable palpation skills are prerequisites for correct measurements (Simmonds & Kumar 1993). In the literature only one study was found assessing inter-rater reliability of IRD measurement by palpation (Bursch 1987) and no studies were found comparing palpation and ultrasonography.

The aims of the present study were to evaluate intra and inter-rater reliability of abdominal palpation, and to compare the results from abdominal palpation with 2D ultrasound imaging of the IRD.

2. Methods

2.1 Design

This is a test–retest study to evaluate the intra and inter-rater reliability of IRD measured by palpation and a criterion validity study using ultrasonography as the gold standard. For the palpation test-retest, two test sessions with two physiotherapists with different experience in the use of the palpation test were conducted. During the first session one of the physiotherapists conducting the palpation test also performed the ultrasound measurements.

2.2 Participants

The participants were recruited from a private physiotherapy clinic and among colleagues, friends and family. The participants were eligible for the study if they agreed to participate in two testing sessions and were able to perform the abdominal crunch exercise. The study was approved by the Review Board of the Technical University of Lisbon, Faculty of Human Kinetics. Signed informed consent was obtained before participation and the rights of the participants were provided verbally, as well as in written form.

2.3 Assessors

Two physiotherapists conducted the palpation study: one had 31 years of experience as a women's health PT and in palpation of the IRD, the other had 7 years of experience. The palpation tests were performed in random order between the two physiotherapists, and they were blinded to each other's assessments.

The physiotherapist performing the ultrasound imaging was trained by an experienced radiologist.

2.4 Procedure

The subjects were in supine resting position with the knees bent at 90º and feet resting on the plinth, arms alongside the body (Fig. III-1). After instruction in how to perform an abdominal crunch (Fig. III-2) the subjects were asked to raise the head and shoulders upwards until the shoulder blades cleared the table. One physiotherapist placed the fingers vertically on the subject's Linea Alba in a way that fingers widths could fit the distance between the internal borders of the two rectus abdominis muscles. Using the center of the umbilicus as a reference, measurements were taken in two previously marked locations: one being 2 cm above the umbilicus and the other being 2 cm below the umbilicus. After 2 minutes rest the procedure was repeated by the second physiotherapist. After the abdominal palpation, ultrasound images were taken at the same locations and during the same conditions by one of the physiotherapists (Mota et al. 2012).

2.5 Ultrasound imaging

An ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer was used to collect images in brightness mode (B-mode).

During image acquisition the bottom edge of the transducer was positioned to coincide with the corresponding skin marker (Fig. III-3) and moved laterally until the medial borders of both RA muscles were visualized (Mota et al. 2012). The orientation of the transducer was then adjusted to optimize visualization of the image. Images were collected immediately at the end of exhalation, as determined by visual inspection of the abdomen following the recommendations of Teyhen et al. (2008) Additionally, particular attention was paid to the pressure imposed on the probe in order to avoid reflexive response from the participants.

The intra-rater reliability of the same ultrasound images on IRD has been found to be very good with ICC values above 0.90 (Mota et al. 2012.).

The abdominal crunch exercise was started from the resting position and the subjects held the final position of the exercise until told to return to the starting position.

The set of images on both locations (2 cm above and below the umbilicus) were exported in JPG format and analyzed offline by the same investigator, using a customized Matlab code (Image Processing Toolbox, Mathworks Matlab, USA) following the procedures described by Mota et al. (2012).

2.6 Statistical Analyses

The level of agreement on palpation between the two days of measurements (intra-rater) and between the two testers (inter-rater) was determined by means of Spearman's rho and weighted Kappa (Cohen 1968).

The scale from Landis and Koch (Landis & Koch 1977) was used in the classification of the reliability values. Weighted Kappa values under 0.20 were considered poor, 0.21-0.40 fair, 0.41-0.60 moderate, 0.61-0.80 good and 0.81-1 very good.

Mean of IRD measured by ultrasound was used to estimate 95% confidence intervals (CI) for each palpation category (as finger widths) and a one-way ANOVA test was used to compare mean differences (Bø & Finckenhagen 2001). The level of significance was $p < 0.05$.

3. Results

Twenty healthy female volunteers, mean age 29.3 years (range 16-49), body mass index 23.01 BMI kg/m^2 (range 18.90-28.51) and mean parity of 0.7 children (range 0-2), participated in this study. Twelve of the women were in the postpartum period.

All participants returned for the second test after a mean of 3.9 days (SD 3.9) (range 1 - 16). The results of the intra-rater reliability test of palpation for the experienced physiotherapist are presented in Table III-1. There was agreement across days in 32 of the 40 cases (80%). The reliability when measured by Spearman's rho was 0.812 (p<0.01) and weighted Kappa was 0.766.

The results of intra-rater reliability for the less experienced physiotherapist are presented in Table 2. There was agreement in 29 of the 40 cases (72.5%) across days. The reliability when measured by Spearman's rho was 0.764 (p<0.01) and weighted Kappa was 0.732.

The inter-rater reliability of the measurements obtained by palpation by the two physiotherapists is presented in Table III-3. There was agreement between the two physiotherapists in 25 (62.5%) of the cases. The reliability when measured by Spearman's rho was 0.702 (p<0.01) and weighted Kappa was 0.534.

Table 4 displays means and 95% CI of IRD measured by ultrasound for each palpation category for both physiotherapists. There were no differences between these categories (as finger widths) for the experienced physiotherapist, when comparing average IRD measured by ultrasound (f=1.594, df=(4;35), p=0.198). For the less experienced physiotherapist there were significant differences between the palpation categories when comparing average IRD measured by ultrasound (f=7.024, df=(3;36), p=0.01).

4. Discussion

The current study examined the intra and inter-rater reliability on IRD measurements. Our results showed that the intra-rater reliability of palpation can be considered good for both physiotherapists while the inter-rater reliability was moderate. The results for Spearman's rho can be considered good. However, there was a lack of agreement between the two raters, which was not revealed by the use of Spearman's rho.

As expected, the measurements made by the same physiotherapist were more reliable than the measurements made by two different raters. Besides the difference in experience of palpation testing, this may be due to differences in the width of fingers and subjective interpretation of pressure (Bursch 1987).

The only previous study assessing inter-rater reliability (Bursch 1987) concluded that palpation was an unreliable method to assess IRD. This is in contrast to our study. However, the study populations differ as the study by Bursch (1987) assessed postpartum women less than four days after delivery. In addition, different procedures and statistical methods were used. Bursch (1987) tested the inter-rater reliability of palpation in one location on the linea alba, and four physiotherapists with different levels of experience participated. ANOVA for repeated measures were used to analyze the data.

Choosing a gold standard method to test criterion validity is not a simple task. Computed tomography (CT) and magnetic resonance imaging (MRI) are currently considered the methods of choice to examine the abdominal wall. However, these methods are expensive and CT exposes the patient to radiation (Mendes et al. 2007), making it impossible to use in pregnant women. Hence, ultrasonography has been proposed as a safe and non-invasive technique that can be repeated several times (Mendes et al. 2007) during pregnancy. Coldron et al. (2008) used ultrasound to characterize RA changes during the first year postpartum and Mendes et al. (Mendes et al. 2007) claimed ultrasonography to be an accurate method to measure DRA above and at the umbilicus when compared with surgical compass during abdominoplasty. Recently Mota et al. (2012) found very good reliability for IRD measurements with ultrasound.

Given that palpation values 0, 0.5, 1, 1.5 and 2 finger widths allow a numerical interpretation for IRD comparable to the IRD values obtained by ultrasound this study found a lack of correspondence for one physiotherapist and some correspondence for the other physiotherapist. When comparing the IRD values obtained by palpation with the ones obtained by ultrasound, it was found that ultrasound was more responsive for differences in the distance between the two muscles. Ultrasound measures the IRD in mm and such levels of assessment are difficult to detect by palpation. Palpation categorizes results on 4 or 5 point scales with a grading system ranging from 0 to 2 finger widths. Hence, the palpation may not have sufficient responsiveness to differentiate between individuals.

A strength of the present study is the blinding of the two raters to the palpation results, and to all IRD measurements with the ultrasound until the end of the process. The comparison with a gold standard already tested for reliability can also be considered a strength. To ensure external validity, 12 subjects in the postpartum period and 8 subjects with different parity, were included in the study.

The limitations of the present study include the use of only two raters with different experience in palpation of IRD and inclusion of only healthy subjects without any musculoskeletal or neurological symptoms. It may be more difficult to reliably measure subjects with symptoms that can interfere in the performance of the abdominal crunch across the days in the immediate postpartum period. Another limitation of this study may be that it is a convenience sample and that the subgroups are small. This may explain the differences between the two raters when comparing their palpation and ultrasound measurements.

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5. Conclusion

Good intra-rater reliability for palpation of IRD was obtained across days for both an experienced and a less experienced physiotherapist, while inter-rater reliability was moderate. Palpation can be used in clinical practice. However, ultrasound is a more reliable and valid method. The results of the present study suggest that ultrasound should be used in future research of IRD.

Fig. III-1. Rest position and start position for the abdominal crunch exercise. The subject was supine, in the crook lying position, arms resting along the body.

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Fig. III-2. End position for the abdominal crunch exercise. The subject was supine, in the standard crook lying position, hands touching the knees.

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Fig. III-3. Position of the transducer for the ultrasound imaging.

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Table III-1. Experienced physiotherapist palpation intra-rater reliability across 2 days of measurements. N=40

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		Palpation Day 2					
	Number of finger widths	0	0.5	1	1.5	2	**Total**
Palpation Day 1	0	3 (7.5%)	2 (5.0%)	0 (0%)	0 (0%)	0 (0%)	5 (12.5%)
	0.5	0 (0%)	18 (45.0%)	3 (7.5%)	0 (0%)	0 (0%)	21 (52.5%)
	1	0 (0%)	2 (5.0%)	9 (22.5%)	0 (0%)	0 (0%)	11 (27.5%)
	1.5	0 (0%)	0 (0%)	0 (0%)	1 (2.5%)	0 (0%)	1 (2.5%)
	2	0 (0%)	0 (0%)	0 (0%)	1 (2.5%)	1 (2.5%)	2 (5%)
	Total	3 (7.5%)	22 (55%)	12 (30%)	2 (5%)	1 (2.5%)	40 (100%)

Values in the table are frequency and (% of total). On diagonal the shaded cells are the absolute agreement across the days.

Table III-2. Less experienced physiotherapist palpation intra-rater reliability across 2 days of measurements. N=40

		Palpation Day 2				
	Number of finger widths	0	0.5	1	1.5	**Total**
Palpation Day 1	0	5 (12.5%)	1 (2.5%)	0 (0%)	0 (0%)	6 (15%)
	0.5	1 (2.5%)	16 (40.0%)	2 (4.2%)	0 (0%)	19 (47.5%)
	1	0 (0%)	5 (12.5%)	7 (17.5%)	0 (0%)	12 (30%)
	1.5	0 (0%)	0 (0%)	2 (5%)	1 (2.5%)	3 (7.5%)
	Total	6 (15%)	22 (55%)	11 (27.5%)	1 (2.5%)	40 (100%)

Values in the table are frequency and (% of total). On diagonal the shaded cells are the absolute agreement across the days.

Table III-3. Palpation inter-rater reliability between the experienced and the less experienced physiotherapist. N=40

		Palpation from less experienced PT					
	Number of finger widths	0	0.5	1	1.5	2	**Total**
Palpation from experienced PT	0	3 (7.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (7.5%)
	0.5	2 (5%)	14 (35%)	4 (10%)	0 (0%)	0 (0%)	20 (50%)
	1	0 (0%)	4 (10%)	8 (20%)	2 (5%)	0 (0%)	14 (35%)
	1.5	0 (0%)	0 (0%)	1 (2.5%)	0 (0%)	0 (0%)	1 (2.5%)
	2	0 (0%)	0 (0%)	1 (2.5%)	1 (2.5%)	0 (0%)	2 (5%)
	Total	5 (12.5%)	18 (45%)	14 (35%)	3 (7.5%)	0 (0%)	40 (100%)

Values in the table are frequency and (% of total). On diagonal the shading cells are absolute agreement between the two PTs.

Table III-4. IRD measured by ultrasound for each palpation category.

Palpation categories (finger widths)	*N*		Mean		95% CI	
	ME	LE	ME	LE	ME	LE
0	3	5	8.07	5.84	-8.64, 24.78	-1.19, 12.87
0.5	20	18	11.63	10.95	8.17, 15.09	8.01, 13.88
1	14	14	17.08	16.98	12.47, 21.68	12.81, 21.15
1.5	1	3	8.85	23.19	--	8.03, 38.35
2	2	--	14.38	--	-20.60, 49.36	--

Values in the table are mean IRD (mm) with 95% CI in the five categories assessed by palpation.

Legend: N= Number of cases; ME= More Experienced PT; LE= Less Experienced PT.

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Chapter IV

Ultrasound Imaging Transducer Orientation and Translation during Static Positions of Drawing-in and Abdominal Crunch Exercise

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Abstract

The clinical use of ultrasound imaging to assess inter rectus distance (IRD) is increasing; however, the clinical setting may be problematic due to the variability inherent in the environment. As transducer motion interferes with accurate measurement, this study aimed to document the amount of ultrasound transducer motion (orientation and displacement) when ultrasound images are collected for IRD measurements, during static positions of the abdominal crunch and drawing-in exercises. Transducer angular and linear displacement was measured on 20 participants during the two exercises. Means were used to determine discrepancies in transducer motion for each exercise. None of the exercises produced large transducer motions relative to the pelvis, and all findings are within previously established guidelines for acceptable amounts of transducer motion, except the linear motion during abdominal crunch exercise. The ultrasound transducer can be held relatively stationary in a clinical setting, to evaluate IRD during abdominal crunch and drawing-in exercises.

Keywords:

Diastasis, Inter rectus distance, Postpartum, Ultrasonography.

1. Introduction

Diastasis recti abdominis (DRA) has been defined as an impairment characterized by the separation of the two rectus abdominis muscles along the linea alba (Axer, Keyserlingk, & Prescher, 2001; Boissonnault & Blaschak, 1988; Coldron, Stokes, Newham, & Cook, 2008; Noble, 1995). This increased inter rectus distance (IRD) may be present congenitally, but most commonly develops during pregnancy and in the early postpartum period (Boissonnault & Blaschak, 1988; Coldron et al., 2008; Gilleard & Brown, 1996; Liaw, Hsu, Liao, Liu, & Hsu, 2011). Ultrasound imaging has recently been suggested as an useful method to evaluate morphology (Hides, Miokovic, Belavý, Stanton, & Richardson, 2007; Koppenhaver, Hebert, Parent, & Fritz, 2009; Whittaker & Stokes, 2011), assess muscular geometry (Teyhen et al., 2005) and as an indirect measure of muscle activation via changes in muscle thickness (Mannion, Pulkovski, Toma, & Sprott, 2008; Teyhen et al., 2008). Recently, Mota et al. (2012) found ultrasound imaging to be a reliable method for measuring IRD. However the accurate interpretation of ultrasound imaging data collection depends upon maintaining a relatively stationary transducer position during an imaging study, as transducer motion can distort the image and lead to erroneous conclusions (Klimstra, Dowling, Durkin, & MacDonald, 2007a; Whittaker, Warner, & Stokes, 2009; 2010).

No information exists in literature about the best alignment for ultrasound transducer during IRD measurement. Nevertheless a recent systematic review (Kwah, Pinto, Diong, & Herbert, 2013) provides some information about measurement of muscle fascicle lengths and pennation angles that could be extrapolated for IRD measurements. Benard & Becher (2009) showed that muscle fascicle lengths and pennation angles could be underestimated or overestimated if ultrasound probe was not aligned with the plane of the muscles fascicles. To determine this plane two methods are used: positioning the probe perpendicular to the skin (Bénard, Becher, Harlaar, Huijing, & Jaspers, 2009; Noorkoiv, Stavnsbo, Aagaard, & Blazevich, 2010) or adjusting the probe alignment until image quality is optimized (Aggeloussis, Giannakou, Albracht, & Arampatzis, 2010; Bénard et al., 2009; Noorkoiv et al., 2010). This second method is also used for IRD measurements. It is assumed that when an optimized image is reached the probe is aligned with the plane of both RA muscles.

Additionally, the dynamic nature of ultrasound imaging studies undertaken during abdominal exercises may compromise the interpretation of data. As the position and inward pressure of a USI transducer influences both the location and shape of a structure of interest on a USI image, it is logical to assume that accurate measurement and interpretation will be influenced by changes on its orientation to the body surface (Klimstra, Dowling, Durkin, & MacDonald, 2007b). Recent studies suggest that a range of transducer motion between 5º to 10º for angular displacement around the three axes of rotation and 10 mm on one plane of translation (inward/outward transducer motion), may be acceptable without image distorting and/or introducing measurement error (Whittaker et al., 2009; 2010). Keeping these guidelines for acceptable amounts of transducer motion in mind, it is prudent to determine the amount of ultrasound transducer motion that occurs during ultrasound imaging studies undertaken during the assessment of IRD under contraction conditions.

Abdominal crunch has been considered a risk exercise for development of diastasis recti (Blanchard, 2005) but it has also been used to assess abdominal muscle strength and endurance in women during postpartum (Liaw et al., 2011), and it is also the position to asses IRD by palpation (Boissonnault & Blaschak, 1988; Noble, 1995). Lately core training with the drawing-in exercise has been recommended both in the general population (Mannion et al., 2008; Richardson, 1999; Richardson, Hodges, & Hides, 2004) and during pregnancy and after childbirth (Benjamin, van de Water, & Peiris, 2014).

Therefore the purpose of the present study was to accurately measure the amount of ultrasound transducer linear (displacement) and angular (orientation) motion when ultrasound images are collected for IRD measurements during static positions of the abdominal crunch and the drawing-in exercises.

2. Methods

2.1 Participants

Twenty healthy female volunteers participated in this study. Women in the postpartum period (N=10), were recruited. The participants were eligible for the study if they agreed to participate in one testing session and were able to perform two different abdominal exercises. To ensure external validity, 10 women in postpartum period (less then 6 months) and 10 nulliparous women were included in the study. Pregnant women were excluded from the present study.

The study was approved by the University Ethics Committee.

Signed informed consent was obtained before participation and the rights of the participants were provided in verbal and written form.

2.2 Procedures for ultrasound imaging

An ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer was used to collect images in brightness mode (B-mode) by the same examiner. The investigator was a physiotherapist with specific training in image capturing and measuring IRD.

In the resting position the transducer was placed transversely along the midline of the abdomen in one location on the linea alba, at 2 cm above the center of the umbilicus. Initially, the measurement location was marked on the skin in order to standardize the position of the transducer, through an ink mark drawn with the subject in supine resting position with the knees bent at 90º and feet resting on the plinth, arms alongside the body (Figure IV-1).

During image acquisition the bottom edge of the transducer was positioned to coincide with the correspondent ink mark and moved laterally until the medial borders of both RA muscles were visualized. The orientation of the transducer was then adjusted to optimize visualization of the image. Particular attention was paid to the pressure imposed on the transducer in order to avoid reflexive response from the participants.

Still images were obtained with the subjects on two abdominal contraction conditions: 1) drawing-in exercise (Figure IV-1) and 2) abdominal crunch (Figure IV-2). Three images were taken under each condition, as each exercise was repeated three times. The abdominal crunch exercise was started from the resting position and the subjects were instructed to raise the head and shoulders upwards until the shoulder blades cleared the table. Subjects held this position until they were told to return to the resting position. The drawing-in exercise also started from the resting position, and the subjects were instructed to inhale and after exhaling draw in the abdominal musculature towards their spine. Before starting the procedure the subjects were verbally instructed about the correct performance of the two exercises. During the drawing-in the activation of the transversus abdominis muscle was confirmed by placing the transducer laterally between the iliac crest and rib cage (Teyhen et al., 2005). Every contraction was held for three seconds for data collection with a resting time of 6 to 10 seconds between each repetition.

2.3 Procedures for transducer motion analysis

Motion capture was collected with a thirteen camera Qualisys system (model: Oqus-300plus) operating at a frequency rate of 50Hz. The capture volume provided by the cameras enabled a mean camera residual below 0.5mm.

The transducer motion was tracked by means of a customized cluster composed by 4 non-collinear reflective markers fixed to the long axis of the transducer (Figure IV-3) and by 2 additional markers virtually built at the lower extremity of the transducer using a digitizing pointer. Pelvis position was tracked by means of 4 reflective markers applied to both anterior-superior iliac spines and iliac crests (Figure IV-4).

The Visual 3D software (Visual 3D Basic RT, C-Motion, Inc., Germantown, MD) was used for tridimensional reconstruction of the pelvis and the ultrasonography transducer in the resting position (static calibration). The tridimensional reconstruction of the model enabled us to determine the instantaneous position and orientation of the transducer (linear probe sensor cristal array) relative to the pelvis segment. Two local reference coordinate systems were defined: the pelvis reference coordinate system origin was the midpoint between the right and left anterior iliac spines and the transducer reference system origin was located at the midpoint of the two virtual markers on the base of the transducer (Figure IV-4). We have quantified the orientation of the transducer relative to the pelvis around the X-axis (cranial/caudal tilt), Y-axis (medial/lateral tilt) and Z-axis (clockwise/counterclockwise rotation). The translational movement of the transducer along the YZ plane (inward/outward displacement) was calculated through the scalar distance of the midpoint between the two proximal markers placed in the transducer and the midpoint between the right and left anterior-superior iliac spines. The position of the transducer relative to the pelvis during the calibration of the subject (static motion capture) was assumed as zero degrees in all the axes of rotation and zero meters of translation regarding the linear position of the transducer.

2.4 Statistical analysis

Descriptive statistics (mean, standard error of measurement and range of motion) of ultrasound transducer orientation (cranial/caudal tilt; medial/lateral tilt; clockwise/counterclockwise rotation) and displacement (inward/outward displacement) with respect to the pelvis reference coordinate system were calculated.

3. Results

A total of 120 transducer orientations from 20 subjects, 3 repetitions and 2 different abdominal exercises, were used in the analysis.

A summary of the descriptive statistics (mean, standard error of measurement and range) for transducer orientation and translation relative to the pelvis during the two abdominal exercises are presented in Table IV-1.

Figure IV-5 presents raw data for transducer orientation with respect to pelvis local coordinate system (origin) on XY-plane (A), YZ-plane (B) and XZ-plane (C) during the 60 observations (20 participants x 3 trials) on each condition (abdominal crunch and drawing-in).

Frequencies reported in Table 1 refer to the number of times that the transducer was positioned in each direction. During the abdominal crunch the transducer was predominantly placed on X-positive (cranial) and Z-negative (clockwise). A similar frequency was found for Y-Positive (medial) and Y-negative (lateral). During the drawing-in condition, the transducer was predominantly positioned on X-positive (cranial), Y-positive (medial) and Z-negative (clockwise).

For overall directions the mean amplitude of these rotations is less than 5º in both exercises.

Transducer displacement refers to the displacement along the YZ plane with respect to the pelvis. Results showed a mean translation less than 15 mm, in a predominantly outward direction during abdominal crunch. During drawing-in exercise the mean displacement was less than 5 mm.

4. Discussion

The amount of ultrasound transducer motion (orientation and displacement) when ultrasound images are collected for IRD measurements during static positions of the abdominal crunch and the drawing-in exercises, is less than 10 degrees of angular displacement and in the drawing-in exercise the displacement of the transducer is less than 8 mm. The guidelines defined by Whittaker (2009) for acceptable amounts of transducer motion without distorting the image and introducing measurement error are <10º of angular and 8 mm of inward/outward motion (Whittaker et al., 2009). Our results showed that the amount of ultrasound transducer motion (orientation and displacement) when ultrasound images are collected for IRD measurements during the abdominal crunch and the drawing-in exercises are within the guidelines suggested by Whittaker (2009). The only exception is the transducer displacement along the YZ plane during the abdominal crunch, which is less than 15 mm. However during the abdominal crunch the transducer translation along the YZ plane is greater than 8 mm as defined in those guidelines (Whittaker et al., 2009). Whittaker et al. (2010) described the amount of transducer motion during several activities, and our results are also in line with this study for drawing in exercise (Whittaker et al., 2010). However the abdominal crunch was not tested in that study. During the abdominal crunch exercise the participants had to move the upper body, then this may have induced movements under the transducer, and it is possible that the translation along the YZ plane is necessarily bigger. Nevertheless the highest mean value for translation during abdominal crunch in our study is less than 15 mm.

Most studies use one of two methods to determine the alignment of the ultrasound probe with the plane of muscles fascicles (Kwah et al., 2013). One method involves positioning the probe perpendicular to the skin (Bénard et al., 2009), the other method involves adjusting the transducer alignment until image quality is optimized (Aggeloussis et al., 2010; Bénard et al., 2009).

There is limited data on whether the method of image optimization is better than positioning the transducer perpendicular to the skin, so we decided to adjust the transducer until the image quality was optimized (Kwah et al., 2013). During the abdominal crunch the transducer was predominantly moved on the X-positive axis (cranial) and Z-negative axis (clockwise) and during the drawing-in exercise the transducer was predominantly situated on X-positive axis (cranial), Y-positive axis (medial) and Z-negative axis (clockwise). This may be explained by the dynamic nature of these exercises and future studies on the transducer alignment are necessary to describe the best way to measure IRD during these exercises.

In general, there are several potential sources of measurement variability: the subjects, the testing, the instrumentation, and factors such as the instructions from the examiner, participant motivation, and participants' skills and motor control may affect performance in different contractions (Koppenhaver et al., 2009). To mitigate against some of these potential sources of errors the position of the subject, examiner's instructions, the transducer pose (position and orientation), the pressure applied to the transducer on the abdominal wall, and the room temperature were standardized.

This appears to be the first systematic study to investigate the amount of handheld ultrasound transducer motion that occurs when undertaking a dynamic ultrasound imaging study of the IRD during two common abdominal exercises. Although the two exercises produced transducer orientations within the error threshold guidelines, it is not surprising that a greater amount of transducer displacement occurred during the more dynamic exercise (i.e. abdominal crunch) suggesting that conscious efforts to control transducer motion during this type of exercises may be prudent as well as standardizing the evaluation protocol and verbal instructions given to the subjects in order to achieve the similar contractions along the time.

The limitations of this study include the use of a single operator for ultrasound imaging collection and the inclusion of only healthy subjects with no musculoskeletal or neurological symptoms. It may be more difficult to measure subjects with symptoms that can interfere in the performance of the exercises or in the last gestational weeks where wider IRD may require a broader view of the abdominal wall to be able to see both RA muscles on the same image. Because the main goal of this study was to document the amount of ultrasound transducer motion (orientation and displacement) when ultrasound images are collected for IRD measurements during the abdominal crunch and the drawing-in exercises.

Every experimental system is unique and possesses its own measurement properties. Therefore, care must be taken when generalizing the results of this study to other measurement parameters and under different conditions (i.e. examiner experience, participant position and characteristics, dynamic maneuvers, etc.).

5. Conclusion

The findings of the current study suggest that the 2D ultrasound imaging transducer can be held relatively stationary in a clinical setting, to evaluate IRD during static positions of the abdominal crunch and drawing-In exercises. Meaningful values of IRD can be made during these exercises if a similar methodology is employed by a skilled operator.

Table IV-1. Descriptive statistics of ultrasound transducer 3D position and translation on each direction with respect to the pelvis during Abdominal Crunch and Drawing-In (N=20).

Condition	Direction		Frequencies	Amplitude		Translation (mm) along YZ plane (inward/outward)	
				Mean (Range)	SEM	Mean (Range)	SEM
Abdominal Crunch	X	Cranial	49	4.75 (0.95 to 11.89)	0.13	9.9 (-10.3 to 29.4)	0.6
		Caudal	11	-3.26 (-7.60 to -0.33)	0.12	14.7 (5.6 to 24.1)	0.3
	Y	Medial	30	4.71 (0.06 to 11.69)	0.18	10.2 (-9.5 to 29.4)	0.7
		Lateral	30	-2.90 (-6.93 to -0.06)	0.10	1.13 (-10.3 to 25.6)	0.4
	Z	Counter clockwise	20	2.43 (0.53 to 4.54)	0.06	16.1 (5.5 to 25.3)	0.3
		Clockwise	40	-4.84 (-10.97 to -0.27)	0.15	8.1 (-10.3 to 29.4)	0.6
Drawing-In	X	Cranial	49	4.49 (0.27 to 11.61)	0.14	-4.6 (-24.0 to 10.9)	0.4
		Caudal	11	-4.65 (-11.51 to -0.05)	0.21	0.6 (-13.2 to 19.8)	0.6
	Y	Medial	38	4.03 (0.55 to 12.00)	0.14	-3.9 (-24.0 to 16.3)	0.4
		Lateral	22	-1.79 (-4.58 to -0.06)	0.07	-3.2 (-23.3 to 19.8)	0.5
	Z	Counter clockwise	11	1.88 (0.73 to 3.40)	0.05	-2.8 (-13.0 to 4.7)	0.3
		Clockwise	49	-3.21 (-7.83 to -0.05)	0.11	-3.8 (-24.0 to 19.8)	0.4

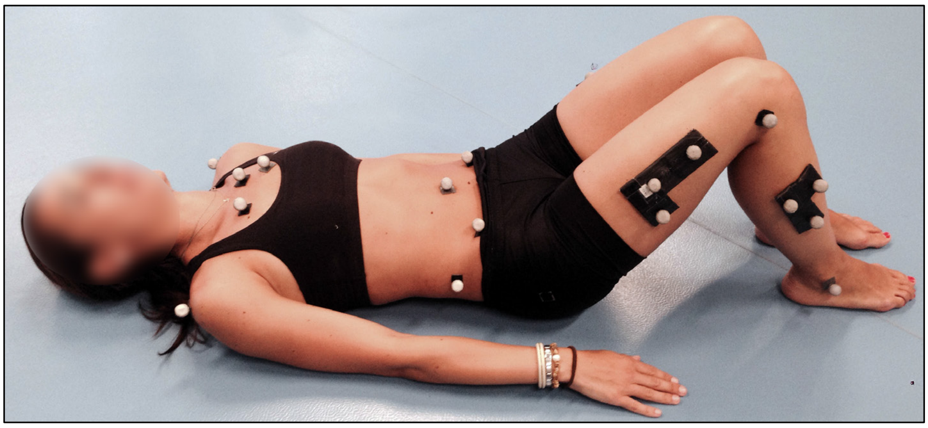

Fig. IV-1. Rest position and the static position of the drawing-in exercise.

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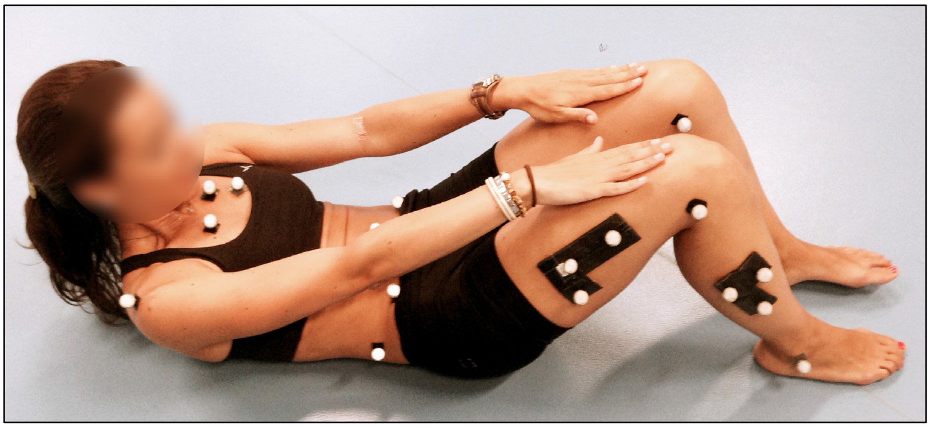

Fig. IV-2. Static position of the abdominal crunch exercise.

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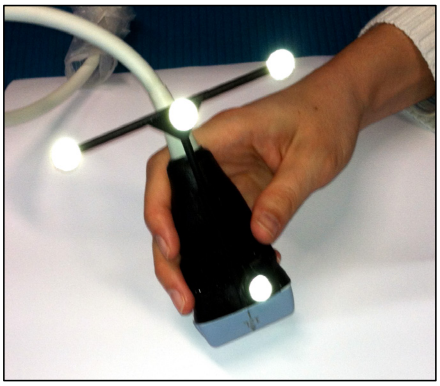

Fig. IV-3. Ultrasound transducer with a customized cluster composed by 4 non-collinear reflective markers fixed to the long axis of the transducer.

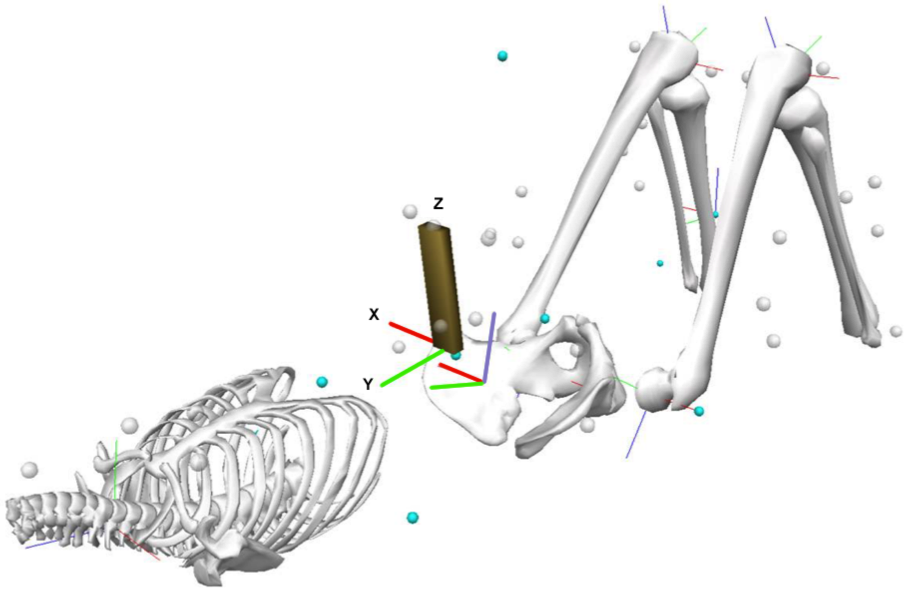

Fig. IV-4. Two local reference coordinate systems were: 1) the pelvis reference coordinate system, which origin was in the midpoint between the right and left anterior iliac spines; 2) transducer reference system which origin was located at the midpoint of the two virtual markers on the base of the transducer.

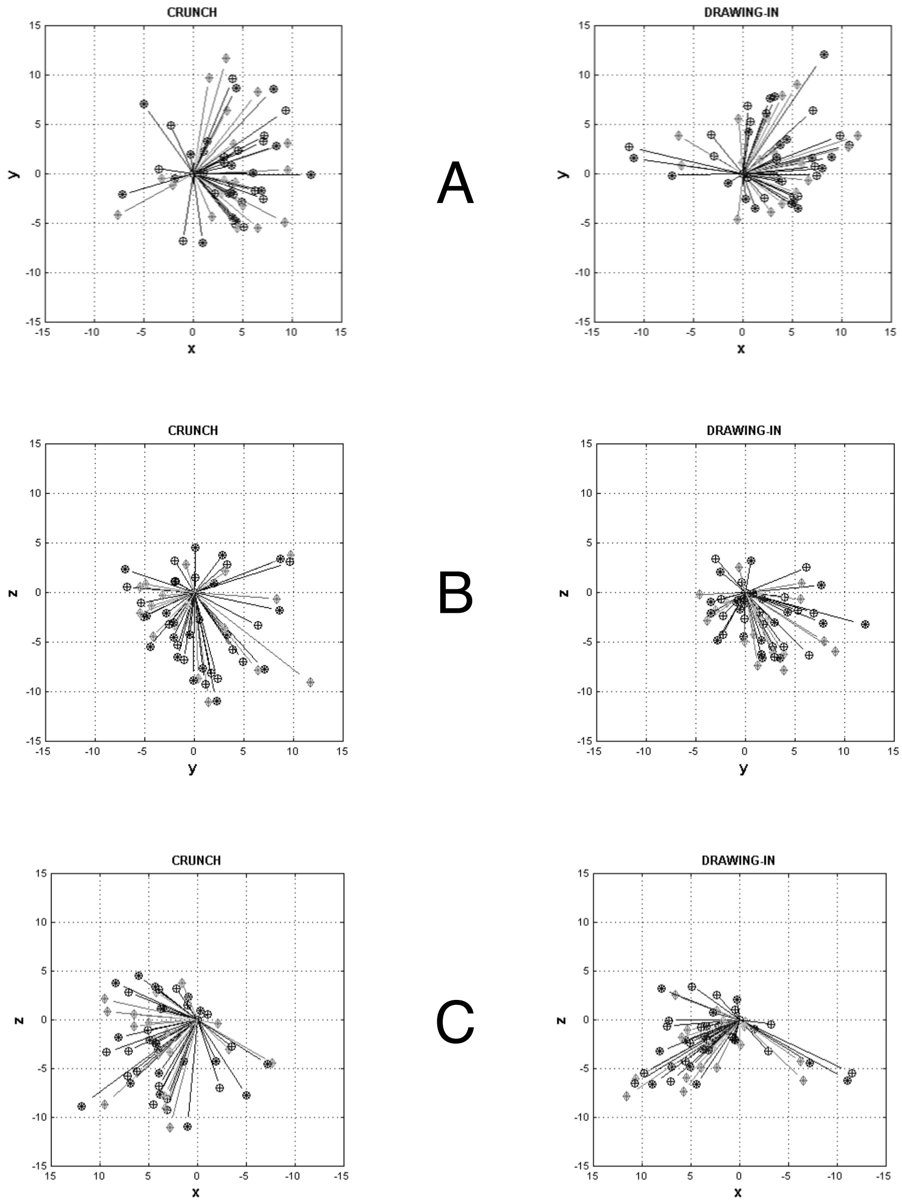

Fig. IV-5. Raw data from transducer orientation with respect to pelvis local coordinate system (origin) on XY-plane (A). YZ-plane (B) and XZ-plane (C) during the 60 observations (20 participants x 3 trials) on each condition (abdominal crunch and drawing in).

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Chapter V

Prevalence and risk factors of Diastasis Recti Abdominis from late pregnancy to 6 months postpartum, and relationship with lumbo-pelvic pain

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Abstract

Diastasis recti abdominis (DRA) is an impairment characterized by a midline separation of the rectus abdominis muscles along the linea alba. It has its onset during pregnancy and the first weeks following childbirth. There is scant knowledge on both prevalence and risk factors for development of the condition.

The aim of this study was to investigate the prevalence of DRA at gestational week 35 and three timepoints postpartum, possible risk factors, and the relationship between DRA and lumbo-pelvic pain.

Ultrasound images of inter rectus distance (IRD) were recorded in 84 healthy primiparous women, at 2 cm below the umbilicus on the linea alba. The IRD was measured at: gestational week 35 and 6-8, 12-14, and 24-26 weeks postpartum. Diagnosis of DRA was defined as 16 mm at 2 cm below the umbilicus. Independent sample t-test and binary logistic regression was used to assess differences and risk factors in women with and without DRA and women with and without lumbo-pelvic pain. $P < 0.05$ was considered statistically significant.

The prevalence of DRA decreased from 100% at gestational week 35 to 39% at 6 months postpartum. No statistically significant differences were found in prepregnancy BMI, weight gain, baby's birth weight or abdominal circumference between women with and without DRA at 6 months postpartum. Women with DRA at 6 months postpartum were not more likely to report lumbo-pelvic pain than women without DRA.

DRA is prevalent at 6 months postpartum, but is not linked with lumbo-pelvic pain.

Keywords:

Abdominal Exercise, Pregnancy, Diastasis Recti, Ultrasound.

1. Introduction

Diastasis recti abdominis (DRA) has been defined as an impairment characterized by the separation of the two rectus abdominis muscles along the linea alba (Axer et al. 2001). This increased inter rectus distance (IRD) may be present congenitally, but most commonly develops during pregnancy and in the early postpartum period (Boissonnault and Blaschak 1988; Gilleard and Brown 1996).

Studies have found that DRA may affect between 30% and 70% of pregnant women (Boissonnault and Blaschak 1988), and that it may remain separated in the immediate postpartum period in 35% to 60% of women (Bursch 1987). However the condition has also been found in 39% of older, parous women undergoing abdominal hysterectomy (Ranney 1990) and in 52% of urogynecological menopausal patients (Spitznagle et al. 2007). Reported prevalence of DRA or increased IRD varies and may be inaccurate due to different cut off points for the diagnosis (Bursch 1987; Boissonnault and Blaschak 1988; Gilleard and Brown 1996; Rath et al. 1996; Chiarello et al. 2005; Spitznagle et al. 2007; Beer et al. 2009) and use of different measurement methods. Most prevalence studies are based on palpation (Bursch 1987; Boissonnault and Blaschak 1988; Mantle et al. 2004) or calipers (Boxer and Jones 1997; Hsia and Jones 2000) which may be less reliable than ultrasonography (Mota et al. 2013). To date there are few studies about the normal width of the IRD in postpartum women (Coldron et al. 2008; Liaw et al. 2011), and there is scant knowledge about risk factors for DRA.

There are some theories stating that failure to treat DRA successfully can lead to long term sequelae (Candido et al. 2005), including abnormal posture (Boissonnault and Blaschak 1988), lumbo-pelvic pain and cosmetic defects (Candido et al. 2005). However, to our knowledge there are no high quality clinical studies to support these statements.

The aims of the present study were to investigate:

1. The prevalence of DRA at gestational week 35, and 6-8, 12-14, and 24-26 weeks postpartum;
2. Possible risk factors related to the presence of DRA at 6 months postpartum;
3. Whether women with DRA at 6 months postpartum have more lumbo-pelvic pain than women without DRA.

2. Methods

This was a longitudinal observational study following first time pregnant women from gestational week 35 till 6 months postpartum.

2.1 Participants

One hundred and twenty-three pregnant women agreed to participate in this study. Women attending pre-natal courses in the Lisbon area were referred to the study by community gynaecologists, physiotherapists, fitness coaches and nurses.

The participants were eligible for the study if they were first time pregnant and agreed to participate in four testing sessions. Exclusion criteria were any kind of conditions affecting the ability to perform daily-living activities or with symptoms that required medical attention e.g., high-risk pregnancies, stillbirth or delivery before gestational week 37, previous spinal or abdominal surgery and neuromuscular diseases. Subjects were also excluded if one of the 4 testing sessions was missed.

The study was approved by the Review Board of the University of Lisbon, Faculty of Human Kinetics. Written informed consent was obtained before participation and the rights of the participants were provided in verbal and written form following the Helsinki declaration.

2.2 Instrumentation and procedures

To assess DRA during pregnancy and postpartum we used a reliable ultrasound method (Mota et al. 2012).

Identification of possible risk factors related to the presence of DRA at 6 months postpartum was based in former published studies (Candido et al. 2005; Spitznagle et al. 2007; Beer et al. 2009; Liaw et al. 2011) and included: women's age, pre-pregnancy body mass index (BMI), weight gain during pregnancy, BMI at 6 months postpartum, hypermobility score, baby weight at birth, abdominal circumference in late pregnancy and level of exercise training.

Lumbo-pelvic pain (low back and pelvic girdle pain (Mørkved et al. 2007) was studied to analyze whether women with DRA at 6 months postpartum have more complaints than women without DRA.

2.3 Ultrasound data collection

An ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer was used to collect images in brightness mode (B-mode) of both rectus abdominis muscles and linea alba. All examinations were done by the same examiner. The investigator was a physiotherapist with specific training in image capturing and measuring IRD.

The transducer was placed transversely along the midline of the abdomen, at 2 cm below the umbilicus center. The measurement location was previously marked on the skin in order to standardize the position of the transducer (Mota et al. 2012).

Still images were collected immediately at the end of exhalation (Teyhen et al. 2008) with subjects in the supine resting position (knees bent at 90º and feet resting on the plinth, arms alongside the body).

The ultrasound images recorded at 4 time points of measurements (gestational week 35, 6-8 weeks postpartum, 12-14 weeks postpartum, and 24-26 weeks postpartum) were exported in Digital Imaging and Communications in Medicine (DICOM) format for further offline processing. The investigator was blinded to the subjects' identification and to the values of the IRD from previous examinations.

2.4 Inter-rectus distance measurement and cut-off point for diastasis recti abdominis

Analyses of 2D ultrasound distances were conducted offline by the same investigator, using a customized code made on specific software (Matlab, Image Processing Toolbox, Mathworks Matlab, USA). Mota et al. (2012) found ultrasound imaging and this procedure to be a reliable method to measure IRD with intra-rater ICC values above 0.90.

Using the definition of Beer et al (2009) the cut-off value for DRA was set at IRD > 16 mm at 2 cm below the umbilicus.

2.5 Anthropometric measurements

Anthropometric parameters included: 1) height (cm) and weight (kg), obtained according the International Society for the Advancement of Kinanthropometry (ISAK) protocol (Marfell-Jones et al. 2012); 2) and the abdominal circumference (cm) measured 2 cm below the umbilicus. The measurements were collected by the same anthropometrist accredited by ISAK, using an anthropometer, a calibrated precision scale (Seca Vogel & Halke, model 761 7019009, Germany) and an anthropometric tape (Rosscraft Innovations, Vancouver, Canada). Gestational weight gain and postpartum weight loss (obtained on the basis of reported pre-pregnancy weight) was calculated for each evaluation moment.

2.6 Joint hypermobility

Hypermobility was defined as four or more positive tests out of nine on Beighton scoring system (Beighton et al. 1973). The tests include 1) passive extension of each 5th finger past 90º; 2) passive apposition of each thumb to the forearm; 3) hyperextension of each elbow past 10º; 4) hyperextension of each knee past 10º; 5) and trunk flexion to allow palms flat on the floor (Beighton et al. 1973). The scoring system has an ICC of 0.75 for intra-observer and 0.78 for inter- observer reliability (Remvig et al. 2007).

2.7 Lumbo-pelvic pain

Low back pain was defined as localized pain in the L2-L5 area with and without radiation to the lower limb. *Pelvic girdle pain* was defined as pain located at the sacroiliac joints, unilaterally or bilaterally and at the pubic symphysis (Grotle et al. 2012). Pain location was assessed with the subjects pointing out the body area in which they had pain and classified in 5 categories: 1) localized low back pain; 2) low back pain with radiation; 3) pain in the pubic symphysis; 4) unilateral sacroiliac joint pain; 5) and bilateral sacroiliac joint pain. Pain intensity was scored on each location as: 0 = “no pain”; 1 = “moderate pain”; 2 = “severe pain” (Bjelland et al. 2013a; 2013b).

Lumbo-pelvic pain was defined as the presence of pain (moderate or severe) at least in one of the assessed locations. The participants were classified as either with or without lumbo-pelvic pain at 6 months postpartum.

2.8 Statistical Analyses

All statistical analyses were made using specific software (IBM-SPSS, Version 21). Background variables and possible risk factors are reported as either means with standard deviation (SD)/ range or numbers and percentages (%). The independent sample t-test or Chi-square test were used to assess the differences in mean values or frequencies between women with and without DRA at 6 months postpartum.

The Cochran's Q Test was used to assess changes in prevalence of DRA between the 4 measurement moments from gestational week 35 until 6 months postpartum. To predict possible risk factors associated with the presence of DRA at 6 months postpartum, binary logistic analysis was performed. The Pearson Chi-Square tests and odds ratios were used to assess the independence between women with and without lumbo-pelvic pain and presence of DRA.

A critical level of $p < 0.05$ was considered statistically significant.

3. Results

Eighty-four of 123 first time pregnant women concluded the longitudinal study (Fig.V-1). Twenty-two women were excluded before the first measurement: 11 because of pregnancy complications, 3 lived too far away to attend the measurements after birth, 6 were not able to meet for the first measurement and 2 for unknown reasons. Seventeen women missed at least one measurement due to personal issues, and were excluded.

The mean age of the 84 participants was 32.1 years (range 25-37) and 81% of the women had undergone university education. They gave birth at mean gestational week 38.8 (range 37-41), 61.9% had vaginal delivery and 38.1% had cesarean sections, and the mean birth weight was 3130 grams (range 2300 to 4000).

At gestational week 35 the mean IRD was 64.6 mm (SD 19.0) and ranged from 22.1 mm to 126.0 mm at rest on measurement 2 cm below the umbilicus, with a prevalence of DRA of 100%. At 6-8 weeks postpartum, the mean IRD at rest was 18.8mm (SD 10.7) with a prevalence of 52.4%. At 12-14 postpartum weeks the mean IRD at rest was 17.2mm (SD 8.9); prevalence of 53.6%, and at 6 months postpartum the mean IRD decreased to 15.3 mm (SD 8.4) with a prevalence of 39.3% of the subjects.

There were significant differences in prevalence of DRA between 6 months postpartum and all the other measurement moments ($p<0.001$).

Background variables and possible risk factors for women with and without DRA at 6 months postpartum are presented in Table V-1. There were no statistically significant differences between groups for any factor.

Table 2 shows the binary logistic analysis to predict possible risk factors associated with the presence of DRA at 6 months postpartum. No significant factors were found in the logistic regression models for DRA at 6 months postpartum.

There were no significant differences in prevalence of lumbo-pelvic pain between women with and without DRA (Table V-3).

4. Discussion

The present study found that prevalence of DRA at 2 cm below the umbilicus decreased from 100% in late pregnancy to 39% at 6 months postpartum. No significant risk factors were found for the presence of DRA at 6 months postpartum. Women with DRA were not more likely to report lumbo-pelvic pain than women without DRA.

Criteria and cut off point for the diagnosis of DRA vary in the literature (Bursch 1987; Boissonnault and Blaschak 1988; Ranney 1990; Gilleard and Brown 1996; Rath et al. 1996; Candido et al. 2005; Spitznagle et al. 2007; Beer et al. 2009; Akram and Matzen 2014), and to date there is no international consensus on the measurement location. In a cadaver study, Rath et al (1996) defined a widening of the IRD more than 10 mm above the umbilicus, 27 mm at the level of the umbilicus and 9 mm below the umbilicus, as pathological DRA. Others defined DRA as a widening of the IRD more than 2.5 cm at one or more assessment points using digital calipers (Chiarello et al. 2005). In a more recent ultrasound study Beer et al (2009) suggest that in nulliparous women, the linea alba should be considered "normal" when the IRD width is less than 15 mm, at the xiphoid level, 22 mm at 3 cm above the umbilicus, and 16 mm at 2 cm below the umbilicus. As Beer et al. (2009) were the only research group using an ultrasound method tested for reliability, we used this definition and chose the location 2 cm below the umbilicus (Mota et al. 2012). The cut-off value for normal IRD proposed by Beer et al (2009) was set for nulliparous women, and may be considered narrow for women during pregnancy and in the postpartum period. However, our prevalence of DRA of 39% is within the range of other prevalence studies (Bursch 1987; Boissonnault and Blaschak 1988; Spitznagle et al. 2007). Published case reports indicate a partial resolution of the DRA at 4 weeks (Hsia and Jones 2000) and 8 weeks postpartum (Boissonnault and Blaschak 1988), which confers with the results of our study, where the prevalence of DRA decreased from 100% during pregnancy to 52.4% at 4-6 weeks after childbirth. Even so, at 6 months postpartum 39% of the women had DRA suggesting that at 6 months postpartum, recovery is still in progress. Unfortunately we have no data beyond this time point.

We did not find any significant risk factors for the presence of DRA at 6 months postpartum with respect to age, BMI before pregnancy and at 6 months postpartum, weight gain during pregnancy, Beighton's hypermobility score, baby weight at birth, abdominal circumference at gestational week 35 or exercise training level before during and after pregnancy**.** As we did not perform an a-priori power calculation for these comparisons, a small sample size may explain the non-significant results. There are few studies for comparison in this area. Candido et al. (2005) found that women with and without DRA did not differ significantly with respect to age, ethnicity, height, weight gain during pregnancy, pre-pregnancy weight, gestational age at delivery, but this study was also limited by the small sample size (Candido et al. 2005). Previous reported studies have found than 10% of pregnant women have severe lumbo-pelvic pain that interferes with daily activities (Fast et al. 1990) and the prevalence of pregnant women suffering from lumbo-pelvic pain is about 20% (Vleeming et al. 2008; Grotle et al. 2012). In the postpartum period reported lumbo-pelvic pain is expected to be high (Parker et al. 2009) and it may affect between 9% and 48% (Bø and Backe-Hansen 2007) of women. The prevalence of these conditions in our study was within the range of other prevalence studies. However we did not perform a detailed pain-history (Fast et al. 1990; Stafne et al. 2012; Robinson et al. 2014) and we did not make any clinical assessment to evaluate the condition, which may underestimate the results. On the other hand, the sample was drawn from a population attending pre-natal courses in private centers, and therefore was not definitive in its ability to delineate prevalence of lumbo-pelvic pain in other populations.

In our study prevalence of lumbo-pelvic pain was similar for women with and without DRA (27.3% and 27.5% respectively). Women with DRA were not more likely to report lumbo-pelvic pain than women without DRA ($p>0.05$). The Odds Ratio observed were approximately 1 (OR = 0.991), showing that women with DRA have the same chances to having lumbo-pelvic pain than those without DRA. This is in line with the results found by Parker et al (2009), who did not find a significant difference between women with and without DRA in lumbo-pelvic pain.

As far as we have ascertained this is the first longitudinal study following a cohort with ultrasound assessment of the IRD from late pregnancy till 6 months post-partum. Other strengths of the study are the number of subjects followed and the use of a reliable ultrasound method to assess IRD with a blinding investigator. The limitations of the study were the lack of pre-pregnancy assessment of the condition and an a-priori power size calculation for comparisons between women with and without DRA. Few subjects in some of the comparison groups may be a limitation of the study, and our results may serve as a source for power calculations for future studies. However, measurement of nulliparous women planning to become pregnant is a challenge in all studies on pregnant women, and there are few studies in this group of women worldwide.

The IRD was the only structural parameter measured in this study, which may not reflect all the structural changes that may take place in the fascial and muscular structures of the abdominal wall in primiparous women. Measurements of other structures (muscle length, thickness), comparison with multiparous women, and a longer follow-up than 6 months postpartum could be of value in future studies.

The IRD cut-off value for categorizing DRA needs to be further observed. As it was established for nulliparous women, it could be interesting to study IRD values for women during pregnancy and postpartum in a large sample size.

5. Conclusion

At 6 months postpartum, 39% of the women were diagnosed with DRA. No risk factors were identified for the presence of DRA in the present study. Women with DRA were not more likely to report lumbo-pelvic pain than women without DRA.

Table V-1. Background variables and potential risk factors for diastasis recti abdominis (DRA) at 6 months postpartum. (P<0.05)

	Women with DRA N=33	**Women without DRA N=51**	**Test**	**P value**
Age *(years)* [Mean (SD)]	31.6 (2.2)	32.5 (2.9)	-1.48 (a)	0.14
BMI before pregnancy *(kg/m^2)* [Mean (SD)]	21.7 (3.5)	22.2 (3.0)	-0.634 (a)	0.53
BMI at 6 months postpartum *(kg/m^2)* [Mean (SD)]	22.3 (3.7)	22.5 (3.2)	-0.266 (a)	0.80
Weight gain during pregnancy *(kg)* [Mean (SD)]	12.8 (3.3)	12.4 (3.5)	0.323 (a)	0.75
Baby weight birth *(Kg)* [Mean (SD)]	3.2 (0.3)	3.1 (0.3)	0.373 (a)	0.71
Abdominal circumference in late pregnancy *(cm)* [Mean (SD)]	105.5 (7.2)	104.7 (7.1)	0.522 (a)	0.60
Hypermobility *(positive >=4 out of 9 on Beighton)* [N (%)]	13 (39.3%)	17 (33.3%)	0.321 (b)	0.57
Vaginal Birth [N (%)]	24 (72.7%)	28 (54.9%)	2.70 (b)	0.10
Regular exercise training *(≥ 3 times per week)* [N (%)]				
• Before pregnancy	17 (51.5%)	25 (49.0%)	0.05 (b)	0.82
• During pregnancy	21 (63.6%)	32 (62.7%)	0.007 (b)	0.93
• At 6 months postpartum	14 (42.4%)	24 (47.1%)	0.174 (b)	0.68

Table V-2. Results of binary logistic analysis to predict possible risk factors associated with the presence of DRA at 6 months postpartum. (P<0.05)

	Coefficient	OR	95% CI for OR	P value
Age *(years)*	-0.127	0.881	(0.743, 1.044)	0.144
BMI *(kg/m^2)* (Pre-pregnancy)	-0.046	0.995	(0.828, 1.101)	0.524
BMI *(kg/m^2)* (6 months postpartum)	-0.018	0.982	(0.862, 1.119)	0.788
Weight gain during pregnancy *(Kg)*	0.023	1.024	(0.899, 1.165)	0.125
Hypermobility	0.046	1.047	(0.877, 1.249)	0.612
Baby weight birth *(positive >=4 out of 9 on Beighton)*	0.261	1.298	(0.334, 5.041)	0.706
Abdominal circumference in late pregnancy at 2cm below the umbilicus *(cm)*	0.004	1.004	(0.953, 1.058)	0.881
Regular exercise training *(≥ 3 times per week)*				
• Before pregnancy	0.100	1.105	(0.460, 2.654)	0.823
• During pregnancy	0.038	1.039	(0.419, 2.577)	0.934
• At 6 months postpartum	-0.188	0.829	(0.343, 2.004)	0.677

Abbreviations: OR= Odds Ratio; CI= Confidence Intervals.

Table V-3. Prevalence of lumbo-pelvic pain and DRA at 6 months postpartum.

Women	With DRA (N = 33)	Without DRA (N=51)	P value	OR
Lumbo-pelvic Pain	N = 9 27.3%	N = 14 27.5%	0.986	0.99 CI 95%: 0.37, 2.65
No Lumbo-pelvic pain	N = 24 72.7%	N = 37 72.5%		

Abbreviations: OR= Odds Ratio; CI= Confidence Intervals.

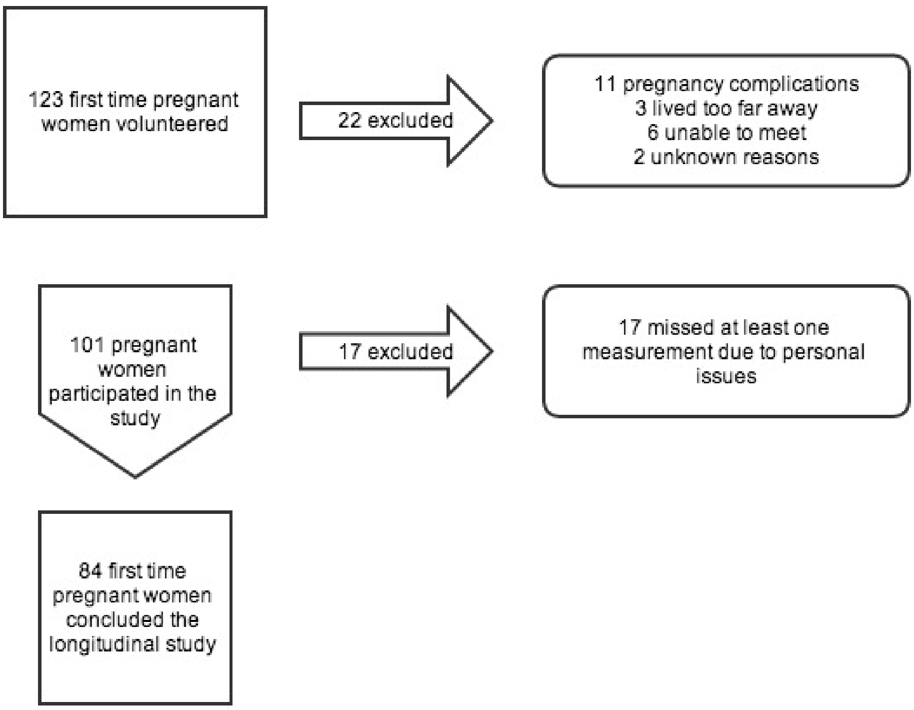

Fig. V-1. Flowchart of the participants in this study.

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Chapter VI

Inter-recti Distance at Rest, During Abdominal Crunch and Drawing in Exercises during Pregnancy and Postpartum

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Abstract

Study design: cross sectional study of first time pregnant women at 4 measurement time points during pregnancy and postpartum period.

Objectives: evaluate inter-recti distance (IRD) at rest and during drawing in and abdominal crunch exercises.

Background: There is scant knowledge about how different abdominal exercises influence IRD in pregnant and postpartum women. There is little evidence on which exercises are most effective in reduction of diastasis recti.

Methods: ultrasound images were recorded in 84 primiparous volunteers with a 12 MHz scanner (GE Logic-*e*) at rest and during drawing in and abdominal crunch, on three different locations on the linea alba. IRD was measured at four time points: gestational week 35-41 and 6-8, 12-14, and 24-26 weeks postpartum. One-way repeated measures ANOVA was performed for each time point to evaluate differences between the 3 conditions.

Results: During pregnancy the IRD decreased in both exercises. During the postpartum period drawing in enlarged the IRD at all locations on the linea alba. These differences were significant at 2 cm below the umbilicus at all three postpartum measurements ($p<0.05$); at 2 cm above the umbilicus at 6 months postpartum ($p<0.001$); and at 5 cm above the umbilicus at 12-14 weeks postpartum ($p=0.003$).

Abdominal crunch significantly reduced IRD ($p<0.05$) during pregnancy and postpartum at every location except 2 cm below the umbilicus at 24-26 weeks postpartum.

Conclusion: The drawing in exercise widened the IRD in postpartum women while the abdominal crunch narrowed the IRD compared to rest both during pregnancy and in the postpartum period.

Keywords:

Abdominal Exercise, Pregnancy, Postpartum, Diastasis Recti, Ultrasound.

1. Introduction

Diastasis recti abdominis (DRA) has been defined as an impairment characterized by a midline separation of the two rectus abdominis muscles along the linea alba.[27,32] This increased inter-recti distance (IRD) has its onset during pregnancy and/or the first weeks following childbirth.[13]

As the fetus grows the two muscle bellies of rectus abdominis, connected by the linea alba, elongate and curve as the abdominal wall expands, and separation of the muscle bellies with protrusion of the umbilicus may occur. [6,11,14,15] Studies have found that DRA may affect between 30% and 70% of pregnant women,[6] and that it may remain separated in the immediate postpartum period in 34.9%[10] to 60% of women.[6,7,8] However the condition has also been found in 38.7% of older, parous women undergoing abdominal hysterectomy[29] and in 52% of urogynecological menopausal patients.[32] It is also seen in men and is thought to be associated with increasing age, weight fluctuations, weight lifting, full sit-ups, familial weakness of the abdominal muscles, chronic or intermittent abdominal distention and conditions which may induce high intra-abdominal pressure.[5,22,26]

Criteria and cut off point for the diagnosis of DRA vary in the literature,[1] and to date there is no international consensus on the measurement location. In a cadaver study, Rath et al (1996) [23] defined a widening of the IRD more than 10 mm above the umbilicus, 27 mm at the level of the umbilicus and 9 mm below the umbilicus, as pathological DRA. Others defined DRA as a widening of the IRD more than 2.5 cm at one or more assessment points using digital calipers[10]. In a more recent ultrasound study Beer et al (2009)[4] suggest that in nulliparous women, the linea alba should be considered “normal” when the IRD width is less than 15 mm, at the xiphoid level, 22 mm at 3 cm above the umbilicus, and 16 mm at 2 cm below the umbilicus.

Published case reports indicate a partial resolution of the DRA at 4 weeks[20] and 8 weeks postpartum[6,11], and there are some theories stating that failure to treat DRA successfully can lead to long term sequelae[9], including abnormal posture[6], lumbo-pelvic pain and cosmetic defects[9]. However, to our knowledge there are no high quality clinical studies to support these statements.

Postnatal women are encouraged to resume abdominal exercises shortly after delivery[15] to improve trunk function and restore abdominal figure and fitness[11]. To date there is scant knowledge on the most effective abdominal exercises both during pregnancy and after childbirth. In particular there is little evidence on which exercises are most effective in reduction of the recti diastasis. Abdominal crunch has been considered a risk exercise for development of diastasis recti,[5] but it has also been used to assess abdominal muscle strength and endurance in women during the postpartum period.[21] Lately core training with the drawing in exercise has been recommended both in the general population[23,30,31] and during pregnancy and after childbirth.[4] It has been proposed that transversus abdominis muscle activation could protect the linea alba and may help to prevent or reduce DRA and speed up recovery.[4] However there are no data to support this suggestion.

The aim of the present study was to compare the IRD measured at rest and during two exercise conditions, drawing in and abdominal crunch exercises, at gestational week 35-41 and at three moments during postpartum: 6-8, 12-14, 24-26 weeks.

2. Materials and Methods

This was a prospective longitudinal observational study following first time pregnant women from gestational week 35 till 6 months of postpartum. For the purpose of the present study we assessed IRD at gestational week 35-41 and 6-8, 12-14, 24-26 weeks postpartum and report cross-sectional results.

2.1 Participants

Women attending pre-natal courses in the Lisbon area were referred to the study by community gynecologists, physiotherapists, fitness coaches and nurses. The participants were eligible for the study if they were first time pregnant, agreed to participate in four testing sessions (one during pregnancy at gestational week 35-41, and three in postpartum) and were able to perform the two different abdominal exercises. Exclusion criteria were any kind of conditions affecting the ability to perform activities of daily living or any symptoms that required medical attention e.g., high-risk pregnancies, stillbirth or delivery before gestational week 37, previous spinal or abdominal surgery and neuromuscular diseases. Women were also excluded if one of the 4 testing sessions was missed. One hundred and twenty-three pregnant women agreed to participate in this study. Eighty-four women concluded all four measurement points. Twenty-two women were excluded before the first measurement: 11 because of pregnancy complications, 3 lived too far away to attend the measurements after birth, 6 were not able to meet for the first measurement and 2 for unknown reasons. Seventeen women were excluded because they missed at least one measurement due to personal issues.

The study was approved by the Review Board of the University of Lisbon, Faculty of Human Kinetics. Written informed consent was obtained before participation and the rights of the participants were protected and were provided in verbal and written form following the Helsinki declaration.

2.2 Instrumentation and Examiner

An ultrasound scanner (GE Logic-*e*) with a 4-12 MHz, 39 mm linear transducer was used on a fixed frequency of 12 MHz, to collect images in brightness mode (B-mode). Before starting the study, the ultrasound protocol and analysis were discussed and practiced with an experienced radiologist. The same investigator did all examinations. The investigator was a physiotherapist with 10 years of experience including specific training in image capturing and 3 years assessing IRD with ultrasound imaging. This investigator was also involved in a test-retest and intra-rater reliability study, to establish the reliability of the ultrasound IRD measurements.[24] During the test-retest study ultrasound images from the rectus abdominis were recorded on 24 healthy female volunteers at rest and on two conditions of abdominal contraction: abdominal crunch and drawing-in exercises. The probe was positioned in two locations: below and above the umbilicus. The blinded investigator measured the IRD offline from two different ultrasound images collected on two different days (test-retest). Additionally, re-analyses of the same ultrasound images were done on two separate occasions (intra-image). Test-retest measurements of IRD demonstrated good to very good reliability with ICC values between 0.74 and 0.90. The only exception was for IRD measured 2 cm below the umbilicus on the abdominal crunch exercise, with an ICC of 0.50. The standard error of measurements (SEM) was between 2.28 to 4.36 mm and the minimal detectable changes (MDCs) ranged from 6.32 to 12.08 mm. For intra-tester reliability of the same images, the ICC values were all above 0.90 with low values of SEM (range 0.65 to 1.99) and MDC (range 1.80 to 4.29).[24]

2.3 Procedures

The ultrasound transducer was placed transversely along the midline of the abdomen at three locations with the center of the umbilicus as a reference: one bellow the umbilicus (2 cm), and two above the umbilicus (2 cm and 5 cm). Initially, each measurement location was marked on the skin in order to standardize the position of the transducer. Ink marks were drawn with the subject in supine resting position with the knees bent at 90º and feet resting on the plinth, arms alongside the body.

During image acquisition the bottom edge of the transducer was positioned to coincide with the correspondent skin marker and moved laterally until the medial borders of both RA muscles were visualized. The orientation of the transducer was then adjusted to optimize visualization of the image. Images were collected immediately at the end of exhalation, as determined by visual inspection of the abdomen following the recommendations of Teyhen et al [34]. Additionally particular attention was paid to the pressure imposed on the probe in order to avoid a reflex response from the participants.

Still images were obtained with subjects in the supine resting position (knees bent at 90º and feet resting on the plinth, arms alongside the body) and on two abdominal contractions: drawing in and abdominal crunch, on this testing order. A single image was taken at each probe location on the linea alba during each contraction. Subjects maintained each exercise contraction for 3-5 seconds for data collection. Abdominal crunch started from the resting position and the subjects were instructed to raise their head and shoulders upwards until their shoulder blades cleared the table. drawing in started from the same resting position. The subjects were instructed to inhale, and after exhaling draw in their navel towards their spine[19]. Before starting the procedure the subjects were verbally instructed about correct performance of the two exercises. All subjects were instructed how to preform drawing in according to procedures described by Richardson et al.[30] During the drawing in maneuver, activation of transversus abdominis was first confirmed by placing the ultrasound transducer laterally between the iliac crest and rib cage and observing the changes in transversus muscle thickness[33]. If necessary, subjects were given visual ultrasound biofeedback to optimize performance of drawing in maneuver, defined as maximal preferential activation of transversus abdominis muscle.[33] Every contraction was held for three seconds with a resting time of 6 to 10 seconds between each repetition.[24] The participants were requested not to practice these two exercises during the study period.

The set of 36 images per subject from each of the 3 conditions (rest, abdominal crunch and drawing in) from the 3 locations (2 cm below and above the umbilicus and 5 cm above the umbilicus) and 4 time points of measurements (gestational week 35 - 41, 6-8 weeks postpartum, 12-14 weeks postpartum, and 24-26 weeks postpartum) were exported in Digital Imaging and Communications in Medicine (DICOM) format for further offline processing. The investigator was blinded to the subjects' identification and to the values of the IRD from previous examinations.

2.4 Inter-recti distance (IRD) measurement

Analyses of 2D ultrasound distances were conducted offline by the same investigator, using a customized code made on specific software (Matlab, Image Processing Toolbox, Mathworks Matlab, USA). Ultrasound images were assumed as a pixel based coordinate system, with the origin in the top left hand corner of the image. In this system an '*x*' and '*y*' coordinate could be used to locate a point in the image and the distance between two or more points could be calculated. On ultrasound images the IRD is characterized by the transverse linear distance from the medial border of rectus abdominis on one side to the corresponding position of its counterpart on the other side. Using this procedure, two points corresponding to the medial borders of both rectus abdominis muscle bellies on the linea alba must be identified on the ultrasound images.[24,25] Mota et al.[24] found ultrasound imaging and this procedure to be a reliable method to measure IRD with intra-rater ICC values above 0.90.

2.5 Statistical Analyses

All statistical analyses were made using specific software (IBM-SPSS, Version 21).

One-way repeated measures analysis of variance (ANOVA) was performed for each measurement time point to evaluate differences between the 3 conditions (rest, drawing in and abdominal crunch). A critical level of $p < 0.05$ was considered statistically significant.

3. Results

Demographic and morphologic data for the participants are presented in Tables 1 and 2. The descriptive statistics for IRD values for each measurement at each location on the linea alba during rest, drawing in and abdominal crunch are shown in Table 3.

The widest IRD values were registered at 2 cm above the umbilicus at rest at gestational week 35-41 (Figure VI-1). The smallest IRD values were measured during abdominal crunch and ranged from 0.37mm to 49.90 mm at 6 months postpartum, at 2 cm below the umbilicus.

At any measurement time point the lowest mean value of IRD registered was during the abdominal crunch exercise (Figure VI-1). The differences between the mean IRD during abdominal crunch and the mean IRD during rest and drawing in were significant ($p<0.05$ in all tests) for all locations on the linea alba. The only exception was at the location 2 cm below the umbilicus compared to rest at 6 months postpartum (Figure VI-1).

At gestational week 35-41 the mean IRD during drawing in was significantly lower than during rest at 2 cm below the umbilicus ($p=0.013$). In the postpartum measurements the mean IRD during drawing in was higher than during rest at all locations on the linea alba. These differences were significant at 2 cm below the umbilicus at all three postpartum measurements ($p<0.05$); at 2 cm above the umbilicus at 6 months postpartum ($p<0.001$); and at 5 cm above the umbilicus at 12-14 weeks postpartum ($p=0.003$).

4. Discussion

The present study demonstrated that during pregnancy and at different time points in the postpartum period the abdominal crunch exercise decreased the mean IRD values compared to rest. The drawing in exercise only significantly decreased the mean IRD values compared to rest during pregnancy in one measurement location. In the postpartum period drawing in resulted in a significant increase of the mean value of the IRD compared to the rest condition.

Transversus abdominis has been described as particularly active during drawing in[33] and it has been suggested that it draws the bellies of the rectus abdominis muscle together.[4] However, in testing this hypothesis, our study found that the IRD increased during execution of this exercise. The result may be explained by the orientation of the transversus muscle fibers and by the attachments of the muscle. Transversus abdominis arises from the thoracolumbar fascia between the iliac crest and the 12th rib at the lateral raphe and the internal aspects of the lower six costal cartilages. The medial attachment of the muscle is a complex and variable bilaminar aponeurosis[17] where some fibers pass medially, where they decussate and blend with the linea alba.[17] In a morphological study it is suggested that the collagen fibril bundles intermingle and form a three-dimensional mesh on the linea alba with three different architectural zones according to the course of collagen fibril bundles.[2] This is also the case in the rectus sheaths and here the number of layers of collagen fibril bundles is variable.[2] In the linea alba 35 to 60% of the fibers were transverse fibers.[2] Maybe because of this fiber orientation, the contraction of transversus abdominis pulls both rectus abdominis laterally. Our findings suggest that transversus abdominis muscle activation during drawing in exercise widens IRD and do not support the hypothesis that drawing in “may prevent or reduce diastasis recti and speed up recovery, allowing women to return to their usual physical and social activities more quickly”.[4]

Although the abdominal crunch has been considered a risk exercise, it is still a common exercise in fitness classes. As an abdominal crunch with Valsalva maneuver might increase intra-abdominal pressure, it may stress the already weakened abdominal wall after pregnancy.[6] Surprisingly, our results showed that the IRD narrows during the execution of abdominal crunch at every location on the linea alba. These results are in line with a previous study in an heterogenic sample of postpartum women.[28] Prior research by Axler and McGill[3] demonstrated that the abdominal crunch presents the highest muscular challenge among 12 different exercises tested. Also Gilleard et al[16] reported that women’s ability to raise their trunk during an abdominal crunch and stabilize the pelvis was compromised during pregnancy. The deficit lasted until 8 weeks postpartum, especially in women with wider IRD during pregnancy. In contrast, our results suggest that an abdominal crunch exercise contributes to a reduction of the IRD.

During pregnancy the location of the widest IRD was measured at 2 cm above the umbilicus. This is in line with the results reported by Liaw et al.[21] and may indicate that below the umbilicus the linea alba has a greater ability to counteract the stress imposed during pregnancy. A possible explanation is that while the collagen fiber architecture above (from xiphoid to umbilicus) and below the umbilicus (from the umbilicus to the symphysis pubis) have a similar 3 dimensional construction consisting of fibers arranged from superficial to deep in an oblique layer,[2,18] below the umbilicus there is a greater amount of transverse fibers providing a greater ability to resist tensile stresses imposed on the linea alba.

According to Wolfe and Davies[12] abdominal strengthening exercises should be done during pregnancy to promote good posture, strengthen the muscles for labor and prevent low back pain and diastasis recti. However, the authors state the need to discontinue abdominal exercise if diastasis recti develops.[12] Our results suggest that abdominal crunch may be more effective in narrowing the IRD than drawing in. Further randomized controlled trials are needed to evaluate the effect of different abdominal exercises on IRD and diastasis recti both during pregnancy and in the postpartum period.

As far as we have ascertained, this is the first study following a cohort of first time pregnant women with ultrasound assessment of the IRD from pregnancy till 6 months postpartum. Strengths of the study are the number of subjects followed, measurement at three abdominal locations, the use of a reliable method to assess IRD and blinding of the investigator. We measured IRD during two commonly used exercises in pregnant and postpartum women.

A limitation of the study is the lack of pre-pregnancy assessment of the condition. However, measurement of nulliparous women planning to become pregnant is a challenge, and there are few studies in this group of women worldwide. On the other hand only one image was taken during rest and during the two exercises and location at each measurement time point. We decided to use only one measurement instead of e.g. mean of three measurements, due to the amount of images and the effort required during the abdominal exercises especially at the first measurement time point during pregnancy.

In our study the only structural parameter measured was the IRD, which may not reflect all of the structural changes that may take place in the fascial and muscular structures of the abdominal wall. The measurements of other structures (muscle length, thickness) could be of value in future research. Based on this study it is suggested that abdominal crunch narrows the IRD and the drawing in widens the IRD. This conclusion is based on the execution of these two exercises at 4 measurement time points during an observational study in pregnancy and in the postpartum period. Further high quality randomized controlled trials on the effect of different abdominal exercises on the DRA are warranted.

5. Conclusion

The IRD showed to be affected by the abdominal isometric contraction involved on abdominal crunch and drawing in exercises, with opposite effects. The drawing in exercise widened the IRD in postpartum and the abdominal crunch narrowed the IRD compared to rest both during pregnancy and in the postpartum period.

5.1 Key Points

Diastasis recti abdominis is a common problem in the post-partum period. The effect of abdominal exercises is of vast interest during pregnancy and after childbirth. In spite of this, there is scant knowledge of how different exercises work on the inter-recti distance and diastasis recti abdominis. Several authors have suggested that the drawing in exercise is a more effective and gentle exercise than the abdominal crunch.

Findings: The present study demonstrated that during pregnancy and in the postpartum period the IRD narrowed when the abdominal crunch exercise was performed. The IRD also narrowed (at 2 cm below the umbilicus) when drawing in exercise was performed during pregnancy. In the postpartum period drawing in resulted in widening of the IRD compared to rest in all locations measured on the linea alba.

Implications: The results of our study do not support the present hypothesis that the drawing in maneuver is an effective exercise during pregnancy and in the post-partum period. There is an urgent need for more basic and experimental studies to understand the mechanisms of different abdominal exercises. In addition, high quality randomized controlled trials on the effect of different abdominal exercises to prevent and treat diastasis recti abdominis are warranted.

Caution: The lack of pre-pregnancy assessment of the condition and sample size should be taken in consideration before generalizing these results.

Table VI-1. Background variables of the study population. Means with range, or number with percentages. (N = 84)

Age *(years)*	32.1 (range 25-37)
Gestational week of birth	38.8 (range 37-41)
Birth weight of baby *(kg)*	3.13 (range 2.3-4.0)
University education	68/84 (81%)
Number with vaginal delivery	52/84 (61.9%)
Number with Caesarean section	32/84 (38.1%)

Table VI-2. Mother's weight, body mass index (BMI), mass (kg)/height(m)^2 and participation in general physical activity (regular exercise classes 2 or more times a week) at each timepoint. Means with standard deviation (SD), or number with percentages. (N=84)

	Before pregnancy*	Gestational week 35-41	Postpartum week 6-8	Postpartum week 12-14	Postpartum week 24-26
Weight *(Kg)*	59.3 (8.9)	71.8 (9.6)	63.0 (9.1)	61.6 (9.7)	60.5 (9.6)
Body Mass Index *(kg/m^2)*	22.0 (3.2)	26.6 (3.4)	23.3 (3.2)	22.8 (3.4)	22.4 (3.4)
Participation in general exercise *(≥2 times per week)**	42/84 (50%)	53/84 (63%)	24/84 (29%)	40/84 (48%)	38/84 (45%)

** Self-reported information.*

Table VI-3. Mean Inter-recti distance in mm with standard deviation (SD) at rest, during drawing in and abdominal crunch at each time point and probe location. (N=84)

	Probe location	Rest	Drawing-in	Abdominal Crunch
Gestational week 35-41	2 cm BU	64.6 (19.0)	60.8 (19.7)	43.7 (14.7)
	2 cm AU	66.9 (19.4)	68.3 (21.6)	49.8 (17.2)
	5 cm AU	61.0 (19.2)	60.9 (18.2)	49.8 (18.7)
Postpartum week 6-8	2 cm BU	18.8 (10.7)	21.8 (12.4)	13.7 (8.6)
	2 cm AU	26.8 (9.3)	27.7 (9.6)	21.2 (6.8)
	5 cm AU	23.0 (9.2)	24.0 (8.8)	18.6 (7.9)
Postpartum week 12-14	2 cm BU	17.2 (8.9)	19.1 (8.9)	13.6 (7.0)
	2 cm AU	23.8 (7.3)	24.2 (7.6)	21.0 (6.0)
	5 cm AU	19.6 (7.8)	22.0 (9.1)	18.1 (8.4)
Postpartum week 24-26	2 cm BU	15.3 (8.4)	17.8 (8.3)	14.9 (8.3)
	2 cm AU	22.4 (7.4)	24.0 (8.1)	19.9 (5.8)
	5 cm AU	18.7 (8.4)	19.4 (8.1)	16.6 (6.8)

Abbreviations: BU= Below the Umbilicus; AU= Above the Umbilicus.

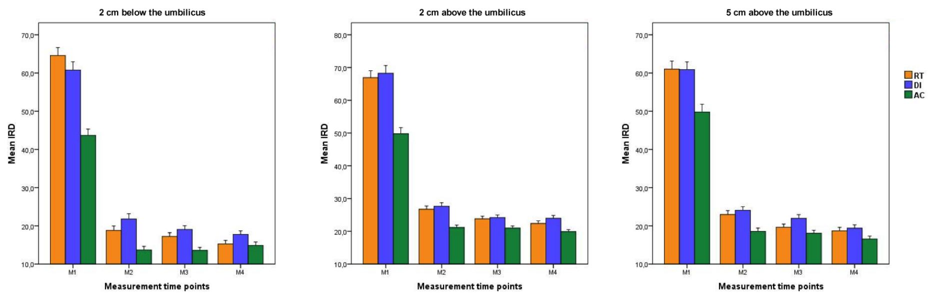

Fig. VI-1. Mean IRD and Standard Error values in mm, at the four measurement time points (M1=gestational week 35 – 41; M2= 6-8 weeks postpartum; M3=12-14 weeks postpartum; M4= 24-26 weeks postpartum), on different abdominal conditions, on each location on the linea alba.

Abbreviations: RT= Rest; DI= Drawing-In; AC= Abdominal Crunch; N= 84.

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Chapter VII

General Discussion

This thesis aimed to provide a better understanding on the adaptations of the abdominal wall, namely to describe the IRD during pregnancy and postpartum period. The approach included two different analyses: 1) to establish a reliable method to evaluate IRD; 2) to describe the IRD from pregnancy till 6 months postpartum, link this condition with other health issues and describe it under different contraction conditions.

In this chapter the main findings are summarized and discussed, though without the detail of the previous presented discussions (chapters II to VI). Strengths and Limitations of this thesis and recommendations for future research are also provided.

1. Summary of main findings

The first study (chapter II) aimed to evaluate test-retest and intra-rater reliability of 2D ultrasound imaging of the IRD at rest and during abdominal crunch and drawing-in exercises. This study demonstrated very good reliability for the intra-tester measurements in the same image for all the conditions tested, with ICC values above 0.90, low values of standard error of measurement (SEM) (range 0.65 to 1.99) and minimal detectable change (MDC) (range 1.80 to 4.29). The test-retest measurements across days showed good reliability during rest and drawing-in exercises below the umbilicus with ICC values of 0.78 and 0.74 respectively and very good reliability during rest, abdominal crunch and drawing-in exercises above the umbilicus with ICC values of 0.87, 0.83 and 0.90 respectively.

The second study presented in chapter III aimed to evaluate intra and inter-rater reliability of abdominal palpation, and to compare the results from abdominal palpation with 2D ultrasound imaging of the IRD.

Palpation showed good intra-rater reliability between days expressed by a weighted Kappa (wK) higher than 0.7 for both physiotherapists, and moderate inter-rater reliability (wK=0.534). Ultrasound was found to be more responsive for differences in IRD compared with values obtained by palpation. As expected, the measurements made by the same physiotherapist were more reliable than the measurements made by two different raters. Ultrasound was more responsive for differences in the distance between the two muscles, and palpation may not have sufficient responsiveness to differentiate between individuals.

The third study presented in chapter IV aimed to describe the amount of ultrasound transducer motion (orientation and translation). The guidelines defined by Whittaker (2009) for acceptable amounts of transducer motion without distorting the image and introducing measurement error are <10º of angular and 8 mm of inward/outward motion. Our results showed that the amount of ultrasound transducer motion (orientation and translation) when ultrasound images are collected for IRD measurements during the abdominal crunch and the drawing-in exercises are within these guidelines. The only exception is the transducer translation along the YZ plane during the abdominal crunch which is greater than 15 mm.

The aims of the longitudinal study presented in chapter V were to investigate: 1) the prevalence of DRA at gestational week 35, and 6-8, 12-14, and 24-26 weeks postpartum; 2) possible risk factors related to the presence of DRA at 6 months postpartum; 3) whether women with DRA at 6 months postpartum have more lumbo-pelvic pain than women without DRA.

The prevalence of DRA decreased from 100% at gestational week 35 to 39% at 6 months postpartum. No statistically significant differences were found in prepregnancy BMI, weight gain, baby's birth weight or abdominal circumference between women with and without DRA at 6 months postpartum. Women with DRA at 6 months postpartum were not more likely to report low back- and pelvic girdle pain than women without DRA.

The aim of the study presented in chapter VI was to compare the IRD measured at rest and during two exercise conditions, drawing in and abdominal crunch exercises, at gestational week 35-41 and at three moments during postpartum: 6-8, 12-14, 24-26 weeks.

This study showed that during pregnancy and at different time points in the postpartum period the abdominal crunch exercise decreased the mean IRD values compared to rest. The drawing in exercise only significantly decreased the mean IRD values compared to rest during pregnancy in one measurement location. In the postpartum period drawing in resulted in a significant increase of the mean value of the IRD compared to the rest condition.

1.1 Procedures and instruments to accurately measure IRD

One of the main outcomes of this thesis is the description of a reliable procedure to assess IRD. The 2D ultrasound imaging proved to be a reliable method to measure IRD in women. Although we suspected that palpation would not be sensitive enough to be used in research we decided to test it, as it is the most common instrument used to assess DRA and most prevalence studies are based on it. We concluded that palpation can be used in clinical practice, but ultrasound is a more reliable and valid method and should be used in research of IRD.

Choosing a gold standard method to test criterion validity is not a simple task. Computed tomography (CT) and magnetic resonance imaging (MRI) are currently considered the methods of choice to examine the abdominal wall. However, these methods are expensive and CT exposes the patient to radiation (Mendes et al., 2007), making it impossible to use in pregnant women. Hence, ultrasonography has been proposed as a safe and non-invasive technique that can be repeated several times (Mendes et al., 2007) during pregnancy.

Ultrasound measures the IRD in mm and such levels of assessment are difficult to detect by palpation.

The dynamic nature of ultrasound imaging studies undertaken during abdominal exercises may compromise the interpretation of data and it is logical to assume that accurate measurement and interpretation will be influenced by changes on the orientation of the transducer (Klimstra et al., 2007).

None of the exercises (abdominal crunch and drawing in) produced large transducer motions relative to pelvis, and all findings are within previously established guidelines for acceptable amounts of transducer motion (<10º of angular and 8 mm of inward/outward motion), except the translation during abdominal crunch exercise. Nevertheless the highest mean value for translation during abdominal crunch in our study is less than 15 mm.

1.2 Changes in IRD from late pregnancy till 6 month postpartum

According to the results of the study presented in chapter V, the prevalence of DRA at 2 cm below the umbilicus decreased from 100% in late pregnancy to 39% at 6 months postpartum. As Beer et al were the only research group using an ultrasound method tested for reliability; we used their definition of normal IRD and chose the location 2 cm below the umbilicus. The cut-off value for normal IRD proposed by Beer et al (2009) was set for nulliparous women, and may be considered narrow for women during pregnancy and in the postpartum period. However, our prevalence of DRA of 39% is within the range of other prevalence studies (Boissonnault & Blaschak, 1988; Bursch, 1987; Spitznagle et al., 2007).

No significant risk factors were found for the presence of DRA at 6 months postpartum. Candido et al. (2005) found that women with and without DRA did not differ significantly with respect to age, ethnicity, height, weight gain during pregnancy, pre-pregnancy weight, gestational age at delivery, but this study was also limited by the small sample size (Candido et al., 2005).

Women with DRA were not more likely to report lumbo-pelvic pain than women without DRA. Previous reported studies have found than 10% of pregnant women have severe lumbo-pelvic pain that interferes with daily activities (Fast et al., 1990) and the prevalence of pregnant women suffering from lumbo-pelvic pain is about 20% (Vleeming et al. 2008; Grotle et al. 2012). In the postpartum period reported lumbo-pelvic pain is expected to be high (Parker et al., 2009) and it may affect between 9% and 48% (Bø & Backe-Hansen, 2007) of women. The prevalence of these conditions in our study was within the range of other prevalence studies. However we did not perform a detailed pain-history (Fast et al., 1990; Robinson, Vøllestad, & Veierød, 2014; Stafne, Salvesen, Romundstad, Stuge, & Mørkved, 2012) and we did not make any clinical assessment to evaluate the condition, which may underestimate the results. On the other hand, the sample was drawn from a population attending pre-natal courses in private centers, and therefore was not definitive in its ability to delineate prevalence of lumbo-pelvic pain in other populations.

1.3 Influence of two abdominal exercises on the IRD

The present study demonstrated that during pregnancy and at different time points in the postpartum period the abdominal crunch exercise decreased the mean IRD values compared to rest. The drawing in exercise only significantly decreased the mean IRD values compared to rest during pregnancy in one measurement location. In the postpartum period drawing in resulted in a significant increase of the mean value of the IRD compared to the rest condition. This was probably the most surprising outcome of this thesis. As core training with the drawing in exercise has been recommended both in the general population (Mannion et al., 2008; Richardson et al., 2004; Richardson, Gwendolen, Hodges, Hides, 1999) and during pregnancy and after childbirth (Benjamin et al., 2014), we were expecting that the activation of the transversus abdominis would draw the bellies of the rectus abdominis muscle together (Benjamin et al., 2014). However, in testing this hypothesis, our study found that the IRD increased during execution of this exercise. The results may be explained by the orientation of the transversus muscle fibers and by the attachments of the muscle and are in line with Brown and McGill (2008).

Also contrary to what we expected, the abdominal crunch which has been considered a risk exercise, and when preformed with Valsalva maneuver might increase intra-abdominal pressure, which may stress the already weakened abdominal wall after pregnancy (Boissonnault & Blaschak, 1988), surprisingly, narrowed the IRD at every location on the linea alba. Our results suggest that abdominal crunch may be more effective in narrowing the IRD than drawing in. The results of our study do not support the present hypothesis that the drawing in maneuver is an effective exercise during pregnancy and in the post-partum period.

There is an urgent need for more basic and experimental studies to understand the mechanisms of different abdominal exercises. In addition, high quality randomized controlled trials on the effect of different abdominal exercises to prevent and treat diastasis recti abdominis are warranted.

2. Strengths and limitations

A strength of this thesis is that in each study the observer was blinded to all the results of IRD measurements until the end of the process. We used a customized Matlab code to implement a method of ultrasound images segmentation based on explicit shape representation defined by a known point distribution model. (Cootes, Taylor, Cooper, & Graham, 1995) We believe that in the near future this Matlab code could be implemented in the software embedded in the ultrasound scanners, helping clinicians to accurately measure the IRD or other muscular morphometric parameters (e.g. muscle cross sectional area).

As far as we have ascertained we have performed the first longitudinal study following a cohort with ultrasound assessment of the IRD from late pregnancy till 6 months postpartum. Other strengths of the study are the number of subjects followed and the use of a reliable ultrasound method to assess IRD during two commonly used exercises in pregnant and postpartum women. Based on this study it is suggested that abdominal crunch narrows the IRD and the drawing in widens the IRD. This conclusion is based on the execution of these two exercises at four measurement time points during an observational study in pregnancy and in the postpartum period. Further high quality randomized controlled trials on the effect of different abdominal exercises on the DRA are warranted.

The limitations of the study were the lack of pre-pregnancy assessment of the condition and an a-priori power size calculation for comparisons between women with and without DRA. Few subjects in some of the comparison groups may be a limitation of the study, and our results may serve as a source for power calculations for future studies. However, measurement of nulliparous women planning to become pregnant is a challenge in all studies on pregnant women, and there are few studies in this group of women worldwide.

The IRD was the only structural parameter measured in this study, which may not reflect all the structural changes that may take place in the fascial and muscular structures of the abdominal wall in primiparous women. Measurements of other structures (muscle length, thickness), comparison with multiparous women, and a longer follow-up than 6 months postpartum could be of value in future studies.

The IRD cut-off value for categorizing DRA needs to be further observed. As it was established for nulliparous women, it could be interesting to study IRD values for women during pregnancy and postpartum in a large sample size.

3. Conclusions

The 2D ultrasound imaging proved to be a reliable method to measure IRD in women. Palpation can be used in clinical practice. However, ultrasound is a more reliable and valid method. We suggest the use of ultrasound imaging in future studies to reliably measure the changes in the IRD during rest, abdominal crunch and drawing-in exercises.

The 2D ultrasound imaging transducer can be held relatively stationary in a clinical setting, to evaluate IRD during abdominal crunch and drawing-in exercises, so conscious efforts to control transducer motion during this kind of exercises may be prudent.

At 6 months postpartum, 39% of the women were diagnosed with DRA. No risk factors were identified for the presence of DRA in the present study. Women with DRA were not more likely to report lumbo-pelvic pain than women without DRA.

The IRD showed to be affected by the abdominal isometric contraction involved on abdominal crunch and drawing in exercises, with opposite effects. The drawing in exercise widened the IRD in the postpartum period and the abdominal crunch narrowed the IRD compared to rest both during pregnancy and in the postpartum period.

Further research

Further studies are needed to evaluate the effect of different abdominal exercises in the reduction of the IRD during the postpartum period. Given the high prevalence and the concern many women experience with this condition, further high quality randomized controlled trials on the effect of different abdominal exercises on the DRA are warranted.

Although ultrasound imaging is a reliable method to assess IRD, data on inter-rater reliability is needed when studies are conducted including more than one investigator.

The IRD was the only structural parameter measured in this study, which may not reflect all the structural changes that may take place in the fascial and muscular structures of the abdominal wall in primiparous women. Measurements of other structures (muscle length, thickness), comparison with multiparous women, and a longer follow-up than 6 months postpartum could be of value in future studies.

The IRD cut-off value for categorizing DRA needs to be further studied. It could be interesting to study IRD values for women during pregnancy and postpartum in a large sample size.

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Apendix I

Published Papers

Apendix II

Thesis related outcomes

Thesis related outcomes

Awards

Dissertation grant from the International Society of Biomechanics.

Papers in international scientific journals

Mota, P., Pascoal, A. G., Sancho, F., & Bø, K. (2012). Test-retest and Intrarater Reliability of 2D Ultrasound Measurements of Distance Between Rectus Abdominis in Women. The Journal of orthopaedic and sports physical therapy, 42(11), 940–946. doi:10.2519/jospt.2012.4115

Mota, P., Pascoal, A. G., Sancho, F., Carita, A. I., & Bø, K. (2013). Reliability of the inter-rectus distance measured by palpation. Comparison of palpation and ultrasound measurements. Manual therapy, 18(4), 294–298. doi:10.1016/j.math.2012.10.013

Mota, P., Pascoal, A. G., Carita, A. I., & Bø, K. (2014). Prevalence and risk factors of Diastasis Recti Abdominis from late pregnancy to 6 months postpartum, and relationship with lumbo-pelvic pain. Manual Therapy (accepted for publication)

Pascoal AG, Dionisio S, Cordeiro F, Mota P. (2014) Inter-rectus distance in postpartum women can be reduced by isometric contraction of the abdominal muscles: a preliminary case-control study. Physiotherapy. doi: 10.1016/j.physio.2013.11.006

Pascoal, A. G., Chityala, R., Mota, P., & Sancho, F. (2012). Ultrasound measurements of the inter-rectus abdominis distance. Journal of Biomechanics, 45(S1), S460.

Sancho, F., Pascoal, A. G., & Mota, P. (2012). An ultrasound study on the effect of exercise on postpartum women inter-rectus abdominis distance. Journal of Biomechanics, 45(S1), S93.

Kim, W., João, F., Tan, J., Mota, P., Vleck, V., Aguiar, L., & Veloso, A. (2013). The natural shock absorption of the leg spring. Journal of Biomechanics, 46(1), 129–136. doi:10.1016/j.jbiomech.2012.10.041

Papers in conference proceedings

Mota, P., Pascoal, A. G., & Vieira, F. (2011). Changes in superficial abdominal muscles morphology during pregnancy: A case study (Vol. Conference Book, p. 30). Presented at the XXII Congress of the International Society of Biomechanics, Brussels.

Carita, A. I., Mota, P., Pascoal, A.G.. Como avaliar a concordância entre instrumentos com escalas de medição distintas? Livro de resumos do XX Congresso Anual da S.P.E.,pp.311-313; Porto (2012).

Pascoal, A. G., Chityala, R., Mota, P., & Sancho, F. (2012). Ultrasound measurements of the inter-rectus abdominis distance. Journal of Biomechanics, 45(S1), S460.

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Mota P, Pascoal AG, Carita I, and Bo K. Diastasis Recovery After Pregnancy. A Follow Up Ultrasound Study On Changes Of Inter-Recti Distance From Late Pregnancy Till 6 Months Postpartum. XXIV Congress of the International Society of Biomechanics, Natal (Brazil), 04 - 09 Agosto, 2013.

Pascoal AG, Sancho F, Mota P, and Bo K. Does The Partial Sit-Up Exercise Reduce The Postpartum Inter-Rectus Abdominis Distance? XXIV Congress of the International Society of Biomechanics, Natal (Brazil), 04 - 09 Agosto, 2013.

Oral communications

Mota, P., Pascoal, A. G., & Vieira, F. (2011). Changes in superficial abdominal muscles morphology during pregnancy: A case study (Vol. Conference Book, p. 30). Presented at the XXII Congress of the International Society of Biomechanics, Brussels.

Pascoal, A. G., Chityala, R., Mota, P., & Sancho, F. (2012). Ultrasound measurements of the inter-rectus abdominis distance. Journal of Biomechanics, 45(S1), S460. ESB 2012: 18th Congress of the European Society of Biomechanics

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Posters in conferences

Kim, W., João, F., Tan, J., Mota, P., Vleck, V., Aguiar, L., & Veloso, A. (2013). The natural shock absorption of the leg spring. ESB 2012: 18th Congress of the European Society of Biomechanics

Mota P, Pascoal AG, Carita I, and Bo K. Diastasis Recovery After Pregnancy. A Follow Up Ultrasound Study On Changes Of Inter-Recti Distance From Late Pregnancy Till 6 Months Postpartum. XXIV Congress of the International Society of Biomechanics, Natal (Brazil), 04 - 09 Agosto, 2013.

Pascoal AG, Sancho F, Mota P, and Bo K. Does The Partial Sit-Up Exercise Reduce The Postpartum Inter-Rectus Abdominis Distance? XXIV Congress of the International Society of Biomechanics, Natal (Brazil), 04 - 09 Agosto, 2013.

Apendix III

PhD Documents