AN INVESTIGATION INTO THE INTER-RATER RELIABILITY OF ULTRASOUND IMAGING OF ABDOMINAL MUSCLES IN ADULTS

Fiona Alston[1] (BSc), Carmen Britz[1] (BSc), Tarryn Du Preez[1] (BSc)
Sandile Mthembu[1] (BSc), Chrissie Pavon[1] (BSc), Natasha Pells[1] (BSc)
Martin Sarembock[1] (BSc), Janeen Hughes[1] (MSc) &
Jennifer Jelsma[1] (PhD)

Correspondence to:
Jennifer Jelsma
Division of Physiotherapy[1],
School of Health and Rehabilitation Sciences
University of Cape Town.
Emaill: Jennifer.jelsma@uct.ac.za

ABSTRACT

Background:

Ultrasound imaging is a non-invasive tool that could be useful in observation of bodily structures, diagnostic purposes, bio-feedback and as an outcome measure. As core stability has become a focal point in rehabilitation, the ability to observe the muscles involved could prove to be clinically useful.

Aim:

This study was therefore conducted to determine the inter-rater reliability of the ultrasound imaging machine.

Methods:

Rectus Abdominus (RA), External Obliquus (EO), Internal Obliquus (IO) and Transversus Abdominus (TrA) were imaged in both a relaxed and a contracted condition. Fifty one participants of thirty years and older were recruited from visitors to a tertiary hospital. Two investigators independently measured the thickness of the abdominal muscles.

Results:

Generally there was a strong relationship when measuring RA, IO and EO, although strong contractions did not meet the criteria set for reliability. RA relaxed had the strongest correlation between raters ($r=0.89$, $p<0.01$) while IO oblique crunch (OC) showed the weakest correlation ($r=0.58$, $p<0.01$. A significant difference was found in thickness from the relaxed state to measuring EO hollowing-in-manoeuvre (HI) ($p=0.02$), Oblique Crunch ($p<0.01$) and RA chin-to-chest ($p<0.01$). Generally, males showed a significantly larger muscle thickness compared to females and a high Body Mass Index (BMI) was associated with unclear images ($p<0.01$).

Conclusion:

The use of the ultrasound imaging machine results in reliable measurement regarding the more superficial muscles in a state of relaxed or moderate activity, even when used by relatively inexperienced therapists. It is recommended that US can be used as a reliable outcome measure of most abdominal muscle activity.

KEY WORDS:

Abdominal muscles, Muscle Thickness, Reliability, Ultrasound Imaging.

Introduction

Ultrasound imaging is fairly new in the rehabilitation sector and it is a useful clinical tool as it allows observation of muscles as they contract (Whittaker, 2004) while providing biofeedback to patients (Bunce, Hough and Moore, 2004). It is an unobtrusive method which permits observation of muscles that are deep and difficult to assess (Whittaker, 2004). Physiotherapists are incorporating ‘core stability’ into rehabilitation and with the shift of focus onto the importance of abdominal muscles, especially Transversus Abdominis (TrA), ultrasound imaging could play a pivotal role in this sector (Teyhen et al., 2005).

The abdominal muscles are important for lumbar spine and pelvic movement and with activation prepare the spine for loads that will be placed upon it (Cholewicki and Van Vliet, 2001 and Rankin, Stokes and Newman, 2006). The abdominal muscles, from superficial to deep, are Rectus Abdominus (RA), being the thickest at rest; External Obliquus (EO) at 5.9mm; Internal Obliquus (IO) at 9.3mm; and TrA at 5.1mm (Gray, 2002 and Rankin et al., 2006 and Urquhart et al., 2004 and Critchley and Coutts, 2002). According to Watanabe et al. (2004), when using ultrasonography, the thickness of erector spinae decreases during lumbar flexion and increases during extension, indicating a possible link between muscle contraction and muscle thickness. Rankin et al. (2006) found that males have significantly thicker abdominal muscles than females and there is a poor correlation between age and muscle size.

The “gold standard” for assessment of muscle size changes are CT and MRI scans which are time consuming, highly expensive and not always easily obtainable (Bemben, 2002). Ultrasound (US) technology which is more cost effective, safe to use and less time consuming has advanced and can view images of superficial and easily accessible muscles just as accurately as MRI (Bemben, 2002). It is now becoming a popular diagnostic tool and uses high frequency sound waves to provide a visual image of bodily structures which can be captured instantaneously (Wink et al., 2006 and Teyhen et al., 2005). Images can then be stored on the computer and measured at a later stage (Bunce et al., 2004).

For any instrument to be useful it must be valid and reliable. To be valid it should measure what it is supposed to measure and to be reliable it should give consistent results when it is repeated on the same participant under similar conditions (Lwanga, Tye and Ayeni, 1999). Inter-rater reliability implies that the instrument gives similar results when used by different therapists on the same individual.

A study by Sherburn et al. (2005) investigating transabdominal real-time US, aimed to establish the reliability of measurements between raters and between testing occasions. It was found that the intra- and inter-rater reliability was satisfactory and therefore application of diagnostic US was both valid and reliable (Sherburn et al., 2005). In this study, participants were tested in crook-lying (Sherburn et al., 2005). This position is appropriate as the task is performed at low load, which is essential for measurement of muscle activity using US imaging (Ferreira, Ferreira and Hodges, 2004).

The resting measure was captured at the end of quiet expiration followed by the activation measure (Kiesel et al., 2006). According to Whittaker (2007), breathing seems to have an effect on the thickness of the abdominal muscles as during inspiration the diaphragm pushes the abdominal contents into the abdominal muscles, making them longer and thinner, with the opposite occurring during expiration.

Limitations of US imaging are that it only gives a two-dimensional view of the muscle and the small view field influences the accuracy of measuring muscle thickness (Whittaker, 2006 and Hides et al., 2006). In testing voluntary activation of the abdominal muscles, various factors such as motivation and skill learning of the participant can affect the outcome of strength and endurance measures (Ferreira et al., 2004). Therefore assessment would be more accurate if it involved measurement of activity in an automatic task (Ferreira et al., 2004).

As highlighted above there are few studies that look at the reliability of US imaging in observing abdominal muscle thickness, particularly in older adults. In addition, there are few therapists in South Africa who are familiar with this technology and it is of interest therefore to establish the inter-rater reliability of US imaging when used on adult abdominal muscles by relatively researchers who have had no prior experience with US.

Objectives

- To determine the inter-rater reliability of US imaging
- To establish a database of “normal” values for relaxed and contracted abdominal muscle thickness in participants aged 30 years and older to be used as a base for further studies.
- To identify whether body mass index affects the reliability of measurement.

Hypothesis

There is a significant difference and no correlation between the measurements taken by two investigators using US imaging when measuring the thickness of abdominal muscles in adults of 30 years and older.

Methodology

This study used a correlational analytical quantitative research design. A sample of convenience was used as participants were recruited from passersby in the main thoroughfare of the tertiary hospital. The subjects had to be 30 years and older and were excluded if they were hospital patients, or had any of the following conditions:

- Physical disability and congenital deformities of the trunk and/or pelvic region
- Abdominal surgery involving incision of the abdominal muscles including Caesarian Section
- History of stroke
- Pelvic fractures
- Postpartum complications
- Spinal cord injury

Using SPSS Version 8, it was determined that a sample size of 20 is required to detect a correlation of 0.6 with p=0.05 and 80% power, and this number was exceeded.

Instrumentation

All participants completed a questionnaire to identify any exclusion criteria. Weight was measured in kilograms (kg) using a scale and height in meters (m) using a tape measure fixed to the wall. A goniometer placed on the lateral epicondyle of each participants knee was used to standardize the angle of knee flexion at ninety degrees. IN order to ensure that images were taken over the same area, the points on the abdomen, where the US transducer was placed were measured using a tape measure and marked with a whiteboard marker.

A Siemens® Accusonic X150 US imaging machine with a 5.5cm wide band linear array frequency of 5Hz was used to capture B-mode (2-D) real-time images of the four abdominal muscles. Conductive gel was used between the transducer and the skin. The researchers underwent training in the operation of the US machine, followed by practice sessions and a pilot study. The length of the image field was measured using a ruler and the half point marked at the top and bottom of the screen. A piece of thread was attached to these points in order to standardize where the calipers were placed on the image.

Procedure

Approval was obtained from the University of Cape Town Research Ethics Committee and permission from the relevant authorities. A pilot study was conducted using ten participants. It aimed to investigate the positions at which the transducer should be placed, the movements to be performed by the participants, the relevance of the questionnaire, the time allocation for each participant and how the data should be captured.
Data collection was done over four days. Participants were recruited by two of the seven researchers who approached those persons passing by the testing area that appeared to fit the inclusion criteria. The investigator introduced herself, gave an overview of what the study entailed and asked if the person was willing to participate. Two different investigators then gave a detailed description of the study and what was required of participants. If willing, they signed a consent form and completed the questionnaire, all of which were in English and Xhosa. Weight was measured using a digital scale, the height was taken by using a wall mounted tape measure, and waist circumference and hip circumference were obtained using a tape measure applied with no tension by the research assistants. Two measurements were taken and the average was used to calculate the Body Mass Index and the Weight: Height ration. According to the exclusion criteria described above each participant was then either included or excluded in the study.

When in the testing area an explanation of the procedure was given and the participant was asked to expose the abdominal area. They adopted a crook lying position with their arms at their sides, ninety degrees knee flexion and no pillow under the head. Measurements were taken at rest and then with the muscle in an active state. Movements performed were the hollowing-in-manoeuvre (HI), oblique crunch (OC) and chin-to-chest. The instructions given for the HI were to draw in the stomach and flatten the back on the bed. For the OC, to reach over with the right hand to touch the outside of the left knee and for the chin-to-chest, to lift the head off the bed and touch the chin onto the chest. The participants then had to demonstrate each movement.

Placement points for the transducer were measured and marked on the left side of the abdomen. Point A for imaging TrA, EO and IO, during the HI and the OC were measured on the mid axillary line, halfway between the anterior superior iliac spine and the inferior border of the last rib. Point B to measure RA during the chin-to-chest was three centimetres above the centre of the superior edge of the umbilicus. To capture the relaxed images of TrA, EO and IO, the transducer was placed horizontally with the midpoint over point A. Maintaining this point, the contracted image was captured. The participant then performed the HI and the OC. If TrA was not seen the transducer was moved laterally, in the same plane. To capture the relaxed and contracted images of RA the transducer was placed horizontally, with the edge furthest away from the investigator over point B. The transducer was shifted until the linea alba was off the screen and only the edge of the fascia and RA could be seen.

Each muscle was measured at the midpoint of the image, with the calliper cursor placed at the junction of the fascia and the muscle. If a muscle did not reach or tapered off at the midpoint, it was measured on the left side of the image. The length was automatically calculated by the machine.

Three members of the research team operated the US machine. One captured each participant's demographic information onto the US machine and froze and saved each image. The other two, “Investigator A” and “Investigator B” were separately involved in giving instructions of the movements to be performed, measuring and marking the points for the position of the transducer and capturing and measuring the images . Each participant was measured twice, once by each investigator. The order in which the investigators measured each participant was alternated to prevent any bias from occurring.

Statistical analysis

The Body Mass Index (BMI) was calculated using weight divided by height2, and the waist-hip ratio (W:H) was calculated by measuring the circumference of the waist at its narrowest portion and the hips at the widest point by means of a tape measure. The Pearson's correlation co-efficient was used to determine inter-rater reliability. The dependent t-test was used to establish whether there was a significant difference between the two measurements. Descriptive statistics were used to determine investigator A and B's mean values of each muscle in a relaxed and contracted state. The averages of these means were calculated to create a set of ‘normal’ values for four different age groups. The independent t-test was used to determine whether there was a significant difference in muscle thickness between males and females, and in BMI and W:H comparing those with image clarity. In each of these, outliers were excluded by determining the standard deviation and multiplying it by 1.96.

It was decided a *priori* that a correlation in excess of r=.70 and no significant difference between the scores of the raters would indicate reliability. This was to ensure agreement both in terms of the relative ranks of the scores as well as of the magnitude of the values.

Results

A total of 51 participants participated in the study of which 4 were excluded due to having caesarean sections. There were 23 females and 24 males aging from 30 to 69 years. The correlation between the investigators (Table 1) reached the criterion for reliability with the exception of IO OC *(r=0.58, p<0.01)* and TrA OC *(r=0.62, p<0.01)*. The highest correlation co-efficient was for RA relaxed *(r =0.89, p<0.01)* (Figure 1).

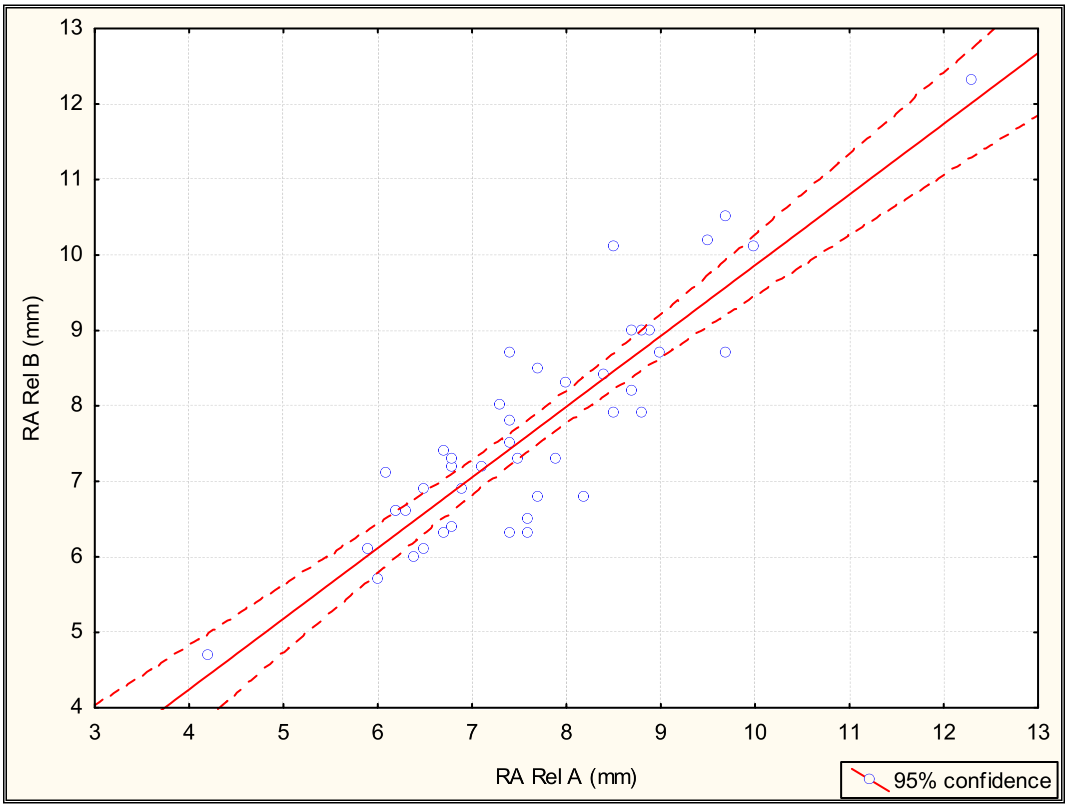

Figure 1: Scatter plot of scores from Rater A and Rater B of the relaxed Rectus Abdominus, the most correlated abdominal muscle measurement

Using the Dependent t-test it was found that EO HI (p=0.02), EO OC (p<0.01) and RA chin-to-chest (p<0.01) showed a significant difference between the investigator's muscle measurements (Table 1).

Table 1: Relationship between abdominal muscle measurements of Investigators 'A' and 'B'

Muscle (mm)	**Muscle state**	**Mean 'A'**	**Std.Dv 'A'**	**Mean 'B'**	**Std.Dv. 'B'**	**N**	**r**	**p for correlation**	**t**	**p for difference**
EO	Relaxed	4.91	1.46	4.67	1.25	45	0.76	<0.01	1.68	0.10
	Hollowing in manoeuvre	***5.38***	***1.77***	***4.94***	***1.67***	***46***	***0.76***	***<0.01***	***2.52***	***0.02***
	Oblique crunch	***5.17***	***2.04***	***4.17***	***1.86***	***43***	***0.75***	***<0.01***	***4.69***	***<0.01***
IO	Relaxed	8.29	2.28	8.11	2.39	47	0.87	<0.01	1.02	0.31
	Hollowing in manoeuvre	9.3	2.77	9.17	2.75	43	0.88	<0.01	0.64	0.53
	Oblique crunch	***12.70***	***4.16***	***12.87***	***3.79***	***34***	***0.58***	***<0.01***	***-0.27***	***0.79***
TrA	Relaxed	3.21	0.71	3.26	0.84	48	0.72	<0.01	-0.57	0.57
	Hollowing in manoeuvre	4.6	1.24	4.75	1.50	42	0.77	<0.01	-0.1	0.32
	Oblique crunch	***4.44***	***1.15***	***4.78***	***1.37***	***28***	***0.62***	***<0.01***	***-1.65***	***0.11***
RA	Relaxed	7.65	1.41	7.66	1.48	44	0.89	<0.01	-0.11	0.91
	Chin-to-chest/ head up	***10.25***	***2.28***	***9.43***	***2.33***	***45***	***0.81***	***<0.01***	***3.86***	***<0.01***

Table 2 shows the mean thickness of the abdominal muscles for all age groups included in the study. These means show that on contraction of the abdominal muscles the thickness of the muscle belly increases with the exception of EO. Across age groups it is evident that there is no common trend with muscle thickness.

Table 2: Mean muscle thickness of males and females for Investigator 'A'

Muscle (mm)	**Muscle state**	**Mean Males**	**Std.Dev. Males**	**Mean Females**	**Std.Dev. Females**	**N Males**	**N Females**	t-value	**p**
EO A	Relaxed	4.93	1.34	5.56	2.17	23	27	-1.2	0.24
EO B	Relaxed	4.63	1.33	4.56	1.35	24	26	0.18	0.86
EO A	Hollowing-in-manoeuvre	5.44	1.81	5.49	1.86	24	26	-0.11	0.92
EO B	Hollowing-in-manoeuvre	5.17	1.78	4.71	1.5	23	26	0.99	0.33
EO A	Oblique crunch	5.31	3.26	5.95	2.75	24	24	-0.73	0.47
EO B	Oblique crunch	4.27	2.24	4.48	2.19	22	24	-0.33	0.74
IO A	Relaxed	9.48	3.29	7.94	1.98	24	26	2.02	0.05
IO B	Relaxed	8.69	2.73	7.70	2.1	24	26	1.44	0.16
IO A	Hollowing-in-manoeuvre	11.22	3.60	8.60	2.29	23	26	3.07	<0.01
IO B	Hollowing-in-manoeuvre	11.0	3.35	8.07	2.17	24	26	3.71	<0.01
IO A	Oblique crunch	13.7	4.54	12.4	4.29	22	21	0.96	0.34
IO B	Oblique crunch	13.87	4.5	12.16	4.78	18	21	1.15	0.26
Tra A	Relaxed	3.40	0.8	3.11	0.65	24	25	1.43	0.16
TrA B	Relaxed	3.73	0.89	2.95	0.78	24	24	3.24	<0.01
TrA A	Hollowing-in-manoeuvre	5.23	1.65	4.42	1.35	22	25	1.85	0.07
TrA B	Hollowing-in-manoeuvre	5.17	1.61	4.44	1.35	22	24	1.68	0.1
TrA A	Oblique crunch	4.71	1.04	4.31	1.31	17	15	0.95	0.35
TrA B	Oblique crunch	5.87	1.67	4.5	1.56	18	20	2.62	0.01
RA A	Relaxed	7.96	1.51	7.41	1.26	24	27	1.42	0.16
RA B	Relaxed	8.03	1.65	7.41	1.34	24	25	1.45	0.15
RA A	Chin-to-chest	10.74	2.68	10.15	2.32	24	27	0.85	0.4
RA B	Chin-to-chest	10.08	2.6	8.97	1.99	23	25	1.68	0.1

* EO = External Obliquus, IO = Internal Obliquus, TrA = Tranversus Abdominus,
RA = Rectus Abdominus, A = Investigator A, B = Investigator B

When comparing mean muscle thickness of males and females (Table 2) it was noted that males generally had a larger muscle thickness than females with the exception of EO. In particular IO HI had a significant difference with both investigator A's *($p<0.01$)* and investigator B's *($p<0.01$)* measurements. TrA relaxed for investigator B was also found to be significant *($p<0.01$)*.

High BMI values were found to be associated with unclear images of the US machine *(p<0.01)*.(See Figures 2 and 3).

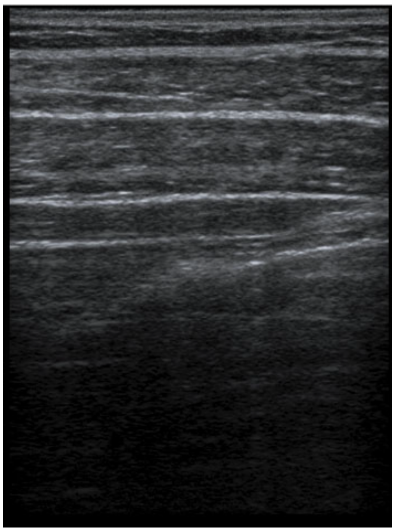

Figure 2: Good clarity ultrasound image of abdominal muscles: EO, IO & TrA

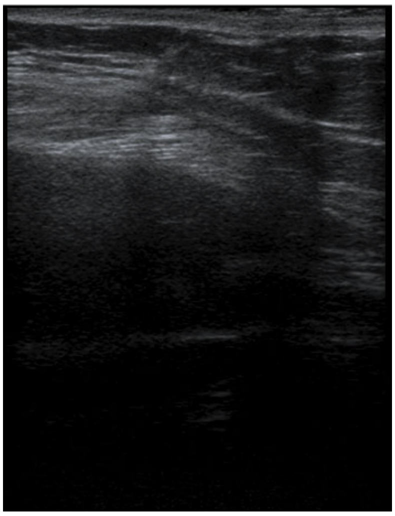

Figure 3: Good clarity ultrasound image of abdominal muscles: EO, IO & TrA

Table 3: Mean muscle thickness of males and females for Investigator 'A'

Muscle (mm)	Muscle state	Mean Males	Std.Dev. Males	Mean Females	Std.Dev. Females	N Males	N Females	t-value	p
EO A	Relaxed	4.93	1.34	5.56	2.17	23	27	-1.2	0.24
EO B	Relaxed	4.63	1.33	4.56	1.35	24	26	0.18	0.86
EO A	Hollowing-in-manoeuvre	5.44	1.81	5.49	1.86	24	26	-0.11	0.92
EO B	Hollowing-in-manoeuvre	5.17	1.78	4.71	1.5	23	26	0.99	0.33
EO A	Oblique crunch	5.31	3.26	5.95	2.75	24	24	-0.73	0.47
EO B	Oblique crunch	4.27	2.24	4.48	2.19	22	24	-0.33	0.74
IO A	Relaxed	9.48	3.29	7.94	1.98	24	26	2.02	0.05
IO B	Relaxed	8.69	2.73	7.70	2.1	24	26	1.44	0.16
IO A	Hollowing-in-manoeuvre	11.22	3.60	8.60	2.29	23	26	3.07	<0.01
IO B	Hollowing-in-manoeuvre	11.0	3.35	8.07	2.17	24	26	3.71	<0.01
IO A	Oblique crunch	13.7	4.54	12.4	4.29	22	21	0.96	0.34
IO B	Oblique crunch	13.87	4.5	12.16	4.78	18	21	1.15	0.26
Tra A	Relaxed	3.40	0.8	3.11	0.65	24	25	1.43	0.16
TrA B	Relaxed	3.73	0.89	2.95	0.78	24	24	3.24	<0.01
TrA A	Hollowing-in-manoeuvre	5.23	1.65	4.42	1.35	22	25	1.85	0.07
TrA B	Hollowing-in-manoeuvre	5.17	1.61	4.44	1.35	22	24	1.68	0.1
TrA A	Oblique crunch	4.71	1.04	4.31	1.31	17	15	0.95	0.35
TrA B	Oblique crunch	5.87	1.67	4.5	1.56	18	20	2.62	0.01
RA A	Relaxed	7.96	1.51	7.41	1.26	24	27	1.42	0.16
RA B	Relaxed	8.03	1.65	7.41	1.34	24	25	1.45	0.15
RA A	Chin-to-chest	10.74	2.68	10.15	2.32	24	27	0.85	0.4
RA B	Chin-to-chest	10.08	2.6	8.97	1.99	23	25	1.68	0.1

* EO = External Obliquus, IO = Internal Obliquus, TrA = Tranversus Abdominus, RA = Rectus Abdominus, A = Investigator A, B = Investigator B

The W:H was found to have no association with image clarity *(p=0.662)* (Table 3).

Table 4: Comparison between BMI and waist-hip ratio with image clarity

	Mean Good Image	Mean Poor Image	N Good Image	N Poor Image	Std. Dev Good image	Std. Dev Poor image	t	p
BMI	24.12	28.51	34	34	4.32	3.35	-3.67	<0.01
W:H	0.84	0.86	34	17	0.089	0.11	-0.44	0.662

Discussion

The results of this study show that the inter-rater use of the US imaging machine met the criteria for reliability in all muscles in the relaxed state. However, the stronger the contraction elicited (e.g. when doing head up for the RA or oblique crunch for the other muscles), the less reliable the measure. This could be as a result of poor reliability or, more likely, as resting measurements were reliable, variation in the patterns of muscle recruitment in the way in which the participants performed these movements from one contraction to the next.

The strongest relationships between investigators values were found when measuring RA, IO and EO. RA relaxed had the strongest correlation. This could be because RA is the most superficial muscle and according to Rankin et al. (2006) the thickest muscle at rest. This assumption is supported by Bemben (2002), who found that diagnostic US is reliable for muscles that are superficial and easily accessible.

The weakest relationship between investigators values was shown with TrA which could be due to it being the deepest muscle thus decreasing the clarity of the image. Upon contraction the thickness of the muscle belly increases, as shown in a study by Watanabe et al. (2004). As the thickness of the muscle belly increases, the depth at which the transducer must penetrate is increased, thereby further affecting image clarity. According to McMeeken et al. (2004), transducers with higher frequencies view superficial structures with great precision and those with lower frequencies view deeper structures, but with poor precision. Adding to the above, the findings from the present study suggest that BMI plays an important part in clarity of the images and precision of the measurements obtained. It was found that participants with a BMI value higher than 28 provided images that were more unclear than those with a BMI lower than 24.

The OC showed the weakest correlation in EO, IO and TrA. This could be because the OC causes the muscle belly to move laterally on the screen making it difficult for the investigators to measure the muscle correctly as the head of the transducer needed to be moved to ensure that the muscle belly was measured.. Another possibility is that as the participants performed the movement the transducer head moved from its original position. The OC is a much larger movement compared to the HI and this may have affected certain participants breathing techniques and thus affected muscle thickness. This is shown in a study by Whittaker (2007) where it was found that during inspiration the abdominal muscles become longer and thinner, while the opposite occurs during expiration. Thus it may have been possible that some participants held their breaths while others didn't.

When comparing the mean muscle thickness between males and females it was found that, as expected, males have larger abdominals for most of the abdominal muscles in both a relaxed and contracted position. This is supported by a study carried out by Rankin et al. (2006) which obtained similar findings.

Limitations and recommendations

There are several limitations to this study that need to be addressed in further research. With regards to the movements performed, participant education and understanding as well as the investigators explanation and language used, could have influenced how the movements were performed. The movements used may not have been the most appropriate to obtain maximal contractions of the muscles; therefore it may be useful to further investigate more reliable movements, especially for EO and IO. It is recommended that static movements for obtaining muscle contraction e.g. resisted neck flexion are preferable to dynamic movements.

In the procedure it is important for the investigator to ensure that the transducer is kept in the same position and knows when and how to move it, should the muscle belly move laterally. Due to the effects of breathing on the abdominal muscles, freezing the image at the same point in the respiratory cycle may allow more accurate comparisons between participants. With reduced image clarity it is necessary to increase the depth of the transducer head so as to ensure viewing of the entire image.

Further study to investigate the stability of the measurement over time should also be undertaken.

Conclusion

This study looked at the inter-rater reliability of US imaging when measuring abdominal muscle thickness and it is concluded that it is a reliable measure of relaxed muscle activity. There is a need to standardise the stronger muscle contractions in terms of activity and strength to improve the reliability of the active measures.

US sound imaging can be used in older patients to reliably investigate the thickness of their muscles under resting and light activity. As it is non-invasive, takes little time to administer and provides reliable information regarding the state of contraction, it is recommended that it should be utilised both as a bio-feedback device and as an outcome measure to assess interventions aimed at recruiting abdominal muscles in an older adult population.

Acknowledgements

Professor Rauf Sayed for statistical support and Dr B. Patel, Mr Lionel Naidoo , Mrs Carolyn Davids for allowing access to the hospital.
University of Cape Town Research Committee for the purchase of the ultrasound machine.

References

Bemben, M.G. (2002). Use of diagnostic ultrasound for assessing muscle size. Journal of Strength and Conditioning Research, 16(1): 103 – 108.

Bunce, S.M., Hough, A.D. and Moore, A.P. (2004). Measurement of abdominal muscle thickness using M-mode ultrasound imaging during functional activities. Manual Therapy, 9(1): 41 – 44.

Cholewicki, J. and van Vliet, J.J. (2001). Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. Clinical Biomechanics, 17(2): 99-105.

Critchley, D.J. and Coutts, F.J. (2002). Abdominal muscle function in chronic low-back pain patients: measurements with real-time ultrasound scanning. Physiotherapy, 86: 322–332.

Ferreira, H., Ferreira, M.L. and Hodges, P.W. (2004). Changes in recruitment of the abdominal muscles in people with low back pain: Ultrasound measurement of muscle activity. Spine, 29(22): 2560-2566.

Gray, H. (2002). Gray's Anatomy. Parragon. Bath, United Kingdom. p: 241 - 248.

Hides, J., Wilson, S., Stanton, W., McMahon, S., Keto, H., McMahon, K., Bryant, M. and Richardson, C. (2006). An MRI investigation into the function of the transverses abdominis muscle during “drawing in” of the abdominal wall. Spine, 31(6): 175-178.

Kiesel, K.B., Uhl, T., Underwood, F.B. and Nitz, A.J. (2006). Rehabilitative ultrasound measurement of select trunk muscle activation during induced pain. Manual Therapy, 13(2): 132-138.

Lwanga, S.K., Tye, C. and Ayeni, O. (1999). Teaching Health Statistics: Lesson and seminar outlines. World Health Organisation. Second edition. p: 14.

McMeeken, J.M., Bieth, I.D., Neham, D.J., Milligan, P. and Critowly, D.J. (2004). The relationship between EMG and change in thickness of transversus abdominis. Clinical Biomechanics, 19(4): 337-342.

Rankin, G., Stokes, M. and Newman, D.J. (2006). Abdominal muscle size and symmetry in normal subjects. Muscle Nerve, 34: 230-236.

Sherburn, M., Murphy, C.A., Carroll, S., Allen, T.J. and Galea, M.P. (2005). Investigation of transabdominal real-time ultrasound to visualise the muscles of the pelvic floor. Australian Journal of Physiotherapy, 51: 167-170.

Teyhen, D.S., Miltenberger, C.E., Deiters, H.M., Del Toro, Y.M., Pulliam, J.N., Childs, J.D., Boyles, R.E. and Flynn, T.W. (2005). The use of ultrasound imaging of the abdominal drawing-in manoeuvre in subjects with low back pain. Journal of Orthopaedic and Sports Physical Therapy, 35: 346-355.

Urquhart, D.M., Barker, P.J., Hodges, P.W., Story, I.H. and Briggs, C.A. (2004). Regional morphology of the transversus abdominis and obliquus internus and externus abdominis muscles. Clinical Biomechanics, 20: 233-241.

Watanabe, K., Miyamoto, K., Masuda, T. and Shinizu, K. (2004). Use of Ultrasonography to Evaluate of the Erector Spinae Muscle in Maximum Flexion and Extension of the Lumbar Spine. Spine, 29(13): 1472-1477.

Whittaker, J. (2004). Abdominal ultrasound imaging of pelvic floor muscle function in individuals with low back pain. The Journal of Manual & Manipulative Therapy, 12(1): 44-49.

Whittaker, J. (2006). Current Perspectives: The clinical application of ultrasound imaging by physical therapists. The Journal of Manual & Manipulative Therapy, 14(2), Guest Editorial: 73-75.

Whittaker, J.L. (2007). Ultrasound imaging of the lateral abdominal wall muscles in individuals with lumbopelvic pain and signs of concurrent hypocapnia. Manual Therapy, 13(5): 404-410.

Wink, M.H., Wijkstra, H., De La Rosette, J.J. and Grimbergen, C.A. (2006). Review article – Ultrasound imaging and contrast agents: A safe alternative to MRI?, Minimally Invasive Therapy and Allied Technologies, 15(2): 93-100.