Faecal Incontinence: Obstetric Causality

A thesis submitted to the University of Manchester for the degree of Doctor of Medicine in the Faculty of Medical and Human Sciences

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Abstract

A thesis submitted to The University of Manchester by Kirsty Ruth Cattle for the degree of Doctor of Medicine (MD).

Faecal Incontinence: Obstetric Causality
2011

Introduction Faecal incontinence is more common in parous women who have had a difficult vaginal delivery. However, the pathophysiology of the injury resulting in faecal incontinence in such women is incompletely understood. This study therefore aimed to compare anal canal and pelvic floor parameters between continent and incontinent women and measure these during pregnancy and after delivery in order to more fully understand the initial insult to the pelvic floor.

Methods Anal manometry and fatigue (using a water-filled microballoon) and pelvic floor strength and fatigue (using an air-filled vaginal probe connected to a Peritron) were measured in 30 primiparous women at booking, end of pregnancy and 6 months post partum. Ten of these women also underwent measurement of pelvis size using ultrasound. A further 61 women, 39 incontinent and 22 continent, also underwent these measurements in order to compare pelvic floor parameters between continent and incontinent women.

Results Voluntary contraction of the external anal sphincter (EAS) was significantly lower 11 weeks post partum than antenatal values (106.5 ± 43.6 cmH₂O antenatally vs 75.5 ± 45.6 cmH₂O post partum, p < 0.001) but there was no significant difference between antenatal values and those measured 6 months post partum (p = 0.24). Anal fatigue rate was significantly slower 11 weeks post partum (p = 0.001), but by six months post partum the difference is no longer significant (p = 0.053). Pelvic floor muscle (PFM) strength fell with age and was significantly lower in incontinent women (8.97 ± 12.88 cmH₂O) than in continent women (27.17 ± 18.16 cmH₂O; p < 0.001). PFM fatigue rate was also significantly slower in incontinent women (p = 0.01). The PFM strength was significantly higher in nulliparous than parous women (p = 0.002) and fatigue rate was faster (p = 0.022). PFM strength (p = 0.006) and fatigue rate (p = 0.004) were significantly lower six months post partum when compared with antenatal values. It was shown that pelvis size can be measured using ultrasound and was found to be repeatable, but inaccurate when compared with magnetic resonance imaging. Insufficient numbers were studied to show an effect on pelvic floor function.

Conclusion Vaginal delivery causes impairment of EAS voluntary contraction which appears to have recovered by six months post partum. It also causes impairment of PFM contraction which is persistent at six months post partum. The reduced PFM function seen post partum also occurs in incontinent women, adding to the evidence that childbirth causes the initial insult to the pelvic floor which results in faecal incontinence, either immediately or some years later.
Declaration

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The Author

Previous academic studies

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Previous research experience

Laboratory-based research on the effect of flow on endothelial microtubules, as part of an intercalated year at the University of St. Andrews.
Audit of the use of barium swallow and endoscopy in the investigation of globus pharyngeus as a clinical medical student at the University of Manchester.

Publications

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<th>Term</th>
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<tr>
<td>AuC</td>
<td>Area under the curve</td>
</tr>
<tr>
<td>CPD</td>
<td>Cephalopelvic disproportion</td>
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<tr>
<td>CPR</td>
<td>Cephalopelvic ratio</td>
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<tr>
<td>EAS</td>
<td>External anal sphincter</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>FI</td>
<td>Faecal incontinence</td>
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<tr>
<td>FR</td>
<td>Fatigue rate</td>
</tr>
<tr>
<td>FRI</td>
<td>Fatigue rate index</td>
</tr>
<tr>
<td>IAS</td>
<td>Internal anal sphincter</td>
</tr>
<tr>
<td>KHQ</td>
<td>Kings Health Questionnaire</td>
</tr>
<tr>
<td>MHQ</td>
<td>Manchester Health Questionnaire</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
</tr>
<tr>
<td>MRP</td>
<td>Maximum resting pressure (anal)</td>
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<tr>
<td>MSP</td>
<td>Maximum squeeze pressure (anal)</td>
</tr>
<tr>
<td>PFM</td>
<td>Pelvic floor muscles</td>
</tr>
<tr>
<td>PNTML</td>
<td>Pudendal nerve terminal motor latency</td>
</tr>
<tr>
<td>SVD</td>
<td>Spontaneous vaginal delivery</td>
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<td>US</td>
<td>Ultrasound</td>
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<tr>
<td>VMSP</td>
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1. Introduction
The involuntary loss of flatus or stool is a devastating condition. It leads to social isolation, depression, marital difficulties and can be the triggering factor leading to admission to residential or nursing care. This distressing condition is not, unfortunately, rare. Prevalence reported in the literature varies, partially because of varying definitions and partially because of the reluctance of patients to report these symptoms. Leigh and Turnberg found that fewer than half the patients being seen in a tertiary referral gastrointestinal clinic volunteered their symptom of faecal incontinence, preferring to complain of diarrhoea. Having said that, anal incontinence (defined as incontinence of flatus, liquid or solid stool) affects 2 to 24% of the adult population. Faecal incontinence (FI) excludes the involuntary loss of flatus and has a prevalence range of 0.4 to 18%. It is more common among women and incidence increases with age.

The study of and treatment of faecal incontinence is a Cinderella subject. However, the costs involved in the treatment of these patients, both socially and financially to the individual and financially to the health service, are large. This thesis, therefore, aims to look at one of the causes of FI with the ultimate aim of improving understanding of the condition and thereby eventually reducing the prevalence of this condition.

**Normal continence**

The maintenance of continence depends on anatomical and functional factors. Stool is stored in the rectum until a socially acceptable time and place for evacuation. The anal canal is the most distal part of the gastrointestinal tract and measures about 4 cm in length. Its walls consist of the mucosa, the subepithelial tissue, the internal anal sphincter, longitudinal muscle and external anal sphincter. The mucosa is stratified squamous epithelium inferior to the dentate line and columnar epithelium superior to this. The subepithelial tissue consists of connective tissue and the vascular cushions.

The internal anal sphincter (IAS) is the continuation of the circular muscle of the rectum, is columnar in shape and consists of smooth muscle fibres. It has
autonomic innervation from the myenteric plexus as well as separate sympathetic supply from T5-L2 via the hypogastric, and parasympathetic supply from S2 to S4 via the nervi erigentes. The function of the IAS is reflected in resting tone of the anal canal, to which it contributes 50-85%.  

The longitudinal muscle is variable in its size and is a continuation of the smooth muscle of the rectal wall, with striated muscle contributions from the pelvic floor musculature.

The external anal sphincter (EAS) consists of striated muscle and is described as consisting of three parts – deep, superficial and subcutaneous. The EAS has a cylindrical shape in the male, but in the female, the anterior portion is shorter than the posterior portion. The function of the EAS is reflected in the tone generated by voluntary contraction – the maximum squeeze pressure (MSP).

The EAS is innervated by the pudendal nerve, which arises from the anterior rami of S2 to S4, leaves the pelvis via the greater sciatic notch, passes under the lower border of pyriformis, angulates round the ischial spine and sacrospinous ligament to enter the pudendal canal, and from thence into the ischiorectal fossa. The function of the pudendal nerve can be studied by means of electromyography (EMG) or nerve conduction studies (pudendal nerve terminal motor latency, PNTML).

Continence is also aided by the muscles of the pelvic floor, which maintain the angle between the anal canal, which passes inferoposteriorly, and the rectum, which passes inferoanteriorly. The pelvic floor muscles form a bowl-shaped diaphragm and consist of pubococcygeus, puborectalis and iliococcygeus, which together are known as levator ani, and the perineal muscles of ischiocavernosus, bulbospongiosus and transversus perinei superficialis. The urethra, vagina and rectum traverse this diaphragm, through a gap in the pelvic floor termed the levator hiatus. There is some controversy over the actions of levator ani. Wendell-Smith has shown that puborectalis is separate from the levator ani complex, and believes that levator ani contraction causes
compression of the anorectal junction. Others believe that levator ani contraction causes the anorectal junction to open and increased EMG activity in levator ani has been found during defaecation. However, it is thought that acting together, the pelvic floor muscles raise the pelvic floor and compress the traversing urogenital tracts, whereas acting separately individual muscles can have opposing effects: puborectalis supports the anorectal angle and thus aids continence, acting as a flap valve during rises in intraabdominal pressure, whereas those fibres of levator ani which insert into the perineal body, known as pubovaginalis, lift the anterior rectal wall over descending faecal matter, thus aiding defaecation.

The pelvic floor musculature has a complex and variable innervation. Traditionally, it was thought to be innervated by the pudendal nerve with additional direct innervation from S3 and S4. However, a cadaveric study of 12 female pelvises found that the levator ani were innervated by branches of S3-S5 entering the superior surface, without any evidence of pudendal nerve branches entering the levator ani. Innervation of the pelvic floor musculature can also be studied by means of EMG.

Connective tissue support of the pelvic floor consists of sheets of loosely organised collagen, elastin, and smooth muscle, and denser aggregations of collagen termed ligaments. Ligaments of note include the uterosacral ligaments, which support the uterine cervix, and the arcus tendineus fascia pelvis and the arcus tendineus levator ani which provide lateral attachments and support for the pelvic floor musculature. Pelvic floor support is estimated by measuring perineal descent.
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**Table 1.1** Causes of faecal incontinence, adapted from Chatoor *et al.*

2
Aetiology of faecal incontinence

The causes of faecal incontinence are listed in table 1.1. The commonest are trauma (obstetric and iatrogenic), rectal prolapse, spina bifida and pelvic organ prolapse.²

The cause of FI in an individual patient may be obvious, for example a neurological cause for new onset FI after spinal cord injury. However, the cause may not be so obvious. For instance, FI in a diabetic may be related to autonomic neuropathy causing diarrhoea, peripheral neuropathy causing pelvic floor musculature weakness or medication-induced diarrhoea. Similarly, intrarectal intussusception may cause internal anal sphincter dysfunction and subsequent FI, without a symptomatic rectal prolapse. Low resting tone of the anal canal¹⁶ and a thickened IAS on endoanal ultrasound scanning¹⁷ may help to indicate that this is the cause of the incontinence. Changes in stool consistency can also result in FI in a patient with previously subclinical sphincter weakening.

In many patients the aetiology is not obvious, even after investigations have been carried out. In such cases, the FI was termed “idiopathic”.¹⁸ Many of the patients who suffer with idiopathic FI are middle aged women. Evidence is accumulating that the original cause of FI in these women is childbirth.

A woman may develop FI immediately post partum from direct sphincter trauma.¹⁹ FI may not develop until middle age but still be related to sphincter trauma: a study of 124 women who developed FI at least one year after vaginal delivery found that 71% of them had an anal sphincter defect on endoanal ultrasound scanning.²⁰

Vaginal delivery causes damage to the innervation of the pelvic floor¹⁵ with associated changes in the function of the anal sphincters,²¹;²² which is another potential aetiology for the development of post partum FI. Although recovery in the innervation of the pelvic floor is seen,¹⁵ it may be that this initial injury,
combined with the loss of neurones with age\textsuperscript{23,24} causes the onset of FI at a later age.

The aging process itself may also contribute to the development of FI in older women. Research on limb skeletal muscle\textsuperscript{25} and the anal sphincters\textsuperscript{26-28} show that, with age, myosin concentration falls, resting and squeeze pressures fall, evidence of neuropathy increases, the IAS increases in thickness while the EAS decreases in thickness. The menopause may also be important in the onset of symptoms. Oestrogen receptors have been found in the EAS muscle.\textsuperscript{29} The age 50 (close to the mean age of the menopause in UK women) provides a statistically significant cut-off in age-related changes in anal function and innervation in women.\textsuperscript{28}

Therefore, idiopathic FI, often seen in older women, appears to be caused by a combination of factors. The initial injury is vaginal delivery, with the menopause and aging process contributing to the development of symptoms several years after the initial injury. As childbirth appears to be important triggering injury, the next section will explore the effects of childbirth on the pelvic floor in more detail.

**Obstetric effects on pelvic floor**

Vaginal delivery affects the entire pelvic floor. There is evidence of damage to the innervation,\textsuperscript{15} pelvic organ support,\textsuperscript{30} anal sphincters,\textsuperscript{31,32} and pelvic floor musculature.\textsuperscript{33} Given the fact that a fetal head, with an area of 70 to 100 cm\textsuperscript{2}, has to pass through the levator hiatus, which measures 6 to 36 cm\textsuperscript{2} in nulliparous women,\textsuperscript{33} this is unsurprising.

**Symptomatic effects**

Anal incontinence occurs in 6 to 9% of new mothers.\textsuperscript{34-36} New onset FI, excluding flatal incontinence, has been found to have a prevalence of 0.7 to 4% post partum.\textsuperscript{34,35,37,38} The risk of developing FI increases with increasing number of deliveries,\textsuperscript{39,40} but there is evidence of symptomatic improvement at
6 months post partum.\textsuperscript{32,36} Similarly, urinary incontinence can occur as a result of childbirth and has been reported as affecting 30\% of new mothers.\textsuperscript{34} Again, the risk of developing urinary incontinence increases with increasing number of deliveries.\textsuperscript{39}

**Muscle damage**

Damage to the musculature involved in the maintenance of continence can occur to the anal sphincters or the pelvic floor diaphragm.

**(a) Anal**

Anal sphincter damage may be overt or occult. Third degree (tear of perineum including anal sphincter) and fourth degree (tear extending through anal mucosa) obstetric tears can be identified immediately post delivery and occur in 1-5\% of vaginal deliveries.\textsuperscript{19,41} However, Sultan et al\textsuperscript{32} found new sphincter defects on endoanal ultrasound in 35\% of primiparous women post delivery. This was related to new bowel symptoms. This high number may be contributed to by a lack of awareness at that time that the female EAS is anteriorly wedged. This can lead to the interpretation of the normal gap in the EAS high in the anal canal as a sphincter defect. However, later studies have detected new sphincter defects in 29\% of women post vaginal delivery.\textsuperscript{31} FI may, in some patients, therefore, be related to undiagnosed sphincter defects. The morphology of the EAS also differs between nulliparous and parous women on endoanal ultrasound.\textsuperscript{42}

The function of the anal sphincters is also impaired post partum. The maximum resting pressure (MRP) of the anal canal reflects IAS function (see Investigation) and is reduced post partum.\textsuperscript{22,32,43} Those delivered by Caesarean section do not suffer a fall in MRP, but instrumental delivery results in a greater fall in MRP.\textsuperscript{22} A first vaginal delivery causes the greatest fall in MRP, with further smaller falls with subsequent deliveries.\textsuperscript{43} Some studies show a recovery in MRP with time after delivery,\textsuperscript{22} whereas others show no improvement.\textsuperscript{32}
The maximum squeeze pressure (MSP) of the anal canal is a measure of EAS function. This also is reduced after childbirth.\textsuperscript{21,22,32,43,44} Again, no fall was seen after Caesarean section\textsuperscript{21,22} but greater falls were seen as a result of instrumental delivery.\textsuperscript{22,45} A second vaginal delivery causes a further, smaller fall in MSP\textsuperscript{43} and pressures are persistently lower than antenatal values during medium\textsuperscript{32,44} and long term\textsuperscript{44} follow up. There is evidence of some recovery of muscle strength in primiparous women.\textsuperscript{21,22}

(b) Pelvic floor

Turning our attention to pelvic floor musculature as a whole, studies have shown structural and functional changes in levator ani post partum. DeLancey \textit{et al} showed abnormalities in levator ani attachments and muscle bulk on MRI scanning in primiparous women but not in nulliparous women.\textsuperscript{46} These defects were twice as common in women with stress urinary incontinence. Dietz and Lanzarone showed by means of a prospective observational study using three-dimensional ultrasound scanning that such changes are as a result of vaginal delivery.\textsuperscript{47} Pelvic floor strength is reduced postpartum\textsuperscript{15} with greater damage occurring as a result of forceps delivery\textsuperscript{45} and increasing parity.\textsuperscript{39} Again, there is evidence of recovery of muscle strength over subsequent months.\textsuperscript{15}

Nerves

Alteration to the innervation of the anal sphincters and pelvic floor can be studied via electromyography (EMG) or nerve conduction studies of the pudendal nerve – pudendal nerve terminal motor latency (PNTML).

EMG studies have examined changes in the innervation of the pelvic floor musculature and EAS. Allen \textit{et al} found EMG evidence of partial denervation of the pelvic floor in 80% of primiparous women postnatally.\textsuperscript{15} The risk of nerve damage was increased by a longer second stage of labour and high birth weight. EMG changes were found in those delivered by emergency Caesarean section, but not those delivered by elective Caesarean section. Increasing number of vaginal deliveries was found to be related to decreasing amplitude of pelvic floor EMG potentials.\textsuperscript{39} EMG studies of the EAS have found increased
fibre density after vaginal delivery, with greater increases in multiparous women compared with primiparous women.\textsuperscript{21,44}

The PNTML has also been shown to be increased by vaginal delivery\textsuperscript{21,44} and is further increased by a second vaginal delivery.\textsuperscript{43} The risk of prolonged PNTML is increased by higher parity, higher birthweight, instrumental delivery and longer second stage of labour.\textsuperscript{43,44}

The question is why neurological damage should occur as a result of labour. It has been found that perineal descent is associated with increased PNTML.\textsuperscript{48} Descent of the perineum of 2 cm would stretch the pudendal nerve by 20\% over its normal length.\textsuperscript{49,50} A nerve may only be stretched by 7 to 20\% before damage is caused.\textsuperscript{51} However, in perineal descent, the perineum was found to move from 2.0 cm above the ischial tuberosities to 1.2 cm below the tuberosities, giving a potential stretch to the pudendal nerves of more than the 20\% theoretical maximal stretch.\textsuperscript{49} The pudendal nerve is tightly bound by connective tissue as it angulates round the ischial spines to enter the pudendal canal. It is therefore at risk of entrapment at this site.\textsuperscript{52}

This evidence would suggest that perineal descent, either during a lifetime of excessive straining, or prolonged descent during vaginal delivery, causes stretch of the pudendal nerve and hence neuropathic damage to the pelvic floor musculature. However, it is also possible that damage to the nerve, of unknown cause, weakens the pelvic floor and thus causes descent of the perineum, rather than perineal descent causing nerve damage.\textsuperscript{48}

Another possibility, not discussed in the literature, is an ischaemic cause for the neuropathy, rather than it being caused by traction. The prolonged presence of the fetal head in the pelvis may impede blood supply to the pudendal nerves, causing the neuropathic changes seen post delivery. This would be supported by the finding of prolonged PNTML and EMG changes after emergency Caesarean section which are not seen after elective Caesarean section.
There is evidence of recovery of the pelvic floor injury over time after delivery. At two months\textsuperscript{21} and six months\textsuperscript{32} the PNTML was significantly improved from postpartum values. Snooks \textit{et al} conclude that the improvement in PNTML and increased mean fibre density on single fibre EMG studies indicate substantial recovery of the damaged innervation in the first two months postpartum.\textsuperscript{21} Anal canal pressures also recover with time after delivery.\textsuperscript{22}

**Connective tissue**

Vaginal delivery causes disruption of pelvic connective tissue, resulting in increased risk of pelvic organ prolapse after childbirth.\textsuperscript{53} Measurement of perineal descent (see Investigation) has been used as a measure of connective tissue injury in the pelvic floor. Studies have shown significant perineal descent both at rest and on straining immediately postpartum.\textsuperscript{21} Recovery from this injury appears to be possible, with perineal position at rest returning to normal by two months after delivery and by five years perineal position on straining was also normal.\textsuperscript{44} The degree of injury appears to be greater after a longer second stage of labour.\textsuperscript{32} However, further examination of the relationship between connective tissue injury and FI is outwith the scope of this study.

**Investigation**

The investigation of FI is multifaceted, reflecting the multifactorial nature of FI, and is tailored to the individual patient, following an appropriate history and examination.

**Bowel pathology**

Imaging of the bowel mucosa may be important in those in whom FI presents as change in bowel habit where the cause may be a neoplastic or inflammatory lesion.

Rectal sensation may be crudely assessed by distending a balloon in the rectum and asking the patient to report various sensations (first sensation, call
Muscle-related

Assessment of continence-muscles may be functional or anatomical and concentrate on the anal sphincters or pelvic floor musculature.

Sphincter function is assessed by means of anorectal manometry, which measures pressures in the anal canal. Maximum resting pressure (MRP, normal $\geq 45$ cm H$_2$O, usually around 70 cm H$_2$O) is thought to reflect IAS function. Maximum squeeze pressure (MSP, normal around 70 cm H$_2$O) reflects the voluntary action of the EAS, and is generally greater in men than women,$^{56}$ though the resting pressure does not differ between the sexes. In general, anal pressures are lower in patients with FI,$^{57}$ but incontinent patients may have normal manometry,$^{57,58}$ as FI is multifactorial. A variety of measuring techniques are in use.$^{59}$ Endoanal ultrasound gives good discrimination of sphincter morphology and can detect sphincter defects.$^{26,60,61}$

Examination of puborectalis and levator ani structure and function are not routinely carried out in the clinical assessment of the incontinent patient other than by digital examination.

Nerve-related

The innervation of skeletal muscle is examined by means of EMG or nerve conduction tests. EMG has been used in the study of both pelvic floor and EAS innervation. Different techniques give different information. The pudendal nerve innervates the EAS and nerve conduction studies of the pudendal nerve are termed pudendal nerve terminal motor latency (PNTML) measurements.

Concentric needle EMG involves the placement of a fine needle surrounded by a steel cannula within the muscle in question. The potential difference between the needle and cannula is displayed visually and/or audibly and recorded for
later analysis. The normal electrical activity of muscle should be minimal at rest and increase with increasing voluntary contraction. The shape, duration and amplitude of motor unit action potentials are analysed. The voltage of a normal action potential crosses the baseline twice or thrice and is termed bi- or triphasic, respectively. Where the voltage crosses the baseline more often, the action potential is termed polyphasic. This is indicative of neuropathy, because reinnervation of denervated muscle fibres spreads the field of endplates to be innervated by the motoneurone. Polyphasic action potentials are often of longer duration. The amplitude will reflect the number of muscle fibres within the motor unit. Where reinnervation has occurred, the number of muscle fibres per motor unit may be higher, resulting in greater action potential amplitude.62

As voluntary contraction increases, the number of motor units recruited increases also, and the number of action potentials recorded by the concentric needle also increases. The action potentials begin to overlap. During maximal voluntary contraction in healthy muscle, it is impossible to distinguish individual action potentials. This overlap of action potentials from neighbouring motor units is termed a full interference pattern. Where severe denervation has occurred, there is loss of this full interference pattern, as there are fewer motoneurones to produce action potentials.62

Single fibre EMG allows different features of muscle electrical activity to be examined. The tiny surface area of the electrode (25 µm diameter) allows the measurement of activity from between one and three muscle fibres from one motor unit. The time delay between the recorded action potentials reflects neuromuscular transmission time and is termed jitter. This is increased following reinnervation and in neurological disorders. Single fibre EMG also allows estimation of mean fibre density of motor units. Where reinnervation has occurred, increasing numbers of action potentials of muscle fibres within the one motor unit are detectable.62

The pudendal nerve terminal motor latency (PNTML) has been extensively used in the research of FI since 1984,52,63 and is measured by means of a probe
consisting of two stimulating electrodes near the tip and two sensing electrodes positioned around 5 cm distal. It is passed per anally and the tip is held near the ischial spines to stimulate the pudendal nerve transrectally as it passes this area, while the receiving electrodes are positioned in the region of the EAS. The PNTML was shown to be significantly increased among incontinent patients.\textsuperscript{52} It is insensitive, however, because PNTML measures conduction speed in the large, fast-conducting, myelinated neurones\textsuperscript{15,52,63,64} and may remain in the normal range whilst these are preserved. However, it may be relevant in the patient in whom sphincter repair is considered as evidence of denervation is related to poorer long term outcome from surgical treatment of FI.\textsuperscript{65,66}

**Connective tissue**

Health of the connective tissue support is implied from measurement of perineal descent. This was described by Parks in 1966\textsuperscript{9} and studied extensively in the 1980s. The principle of perineal descent is that weakness of the pelvic floor muscles causes an increase in the anorectal angle. This anorectal angle helps to maintain continence by acting as a flap valve. When intraabdominal pressure rises, e.g. coughing or straining, the anterior wall of the rectum is forced down onto the posterior wall of the rectum, which is in turn supported by the pelvic floor musculature. Where this support is lost, sudden rises in intraabdominal pressure can lead to involuntary loss of faecal matter. Descent of the pelvic floor also stretches the nerve supply to this area, causing further damage to the innervation (see above: Aetiology of faecal incontinence).

Perineal descent was initially measured using a St. Mark’s perineometer.\textsuperscript{49} This was used with the patient in the left lateral position and consisted of a fixed metal frame and a sliding measuring cylinder. The metal frame is held against the ischial tuberosities and the measuring cylinder is gently placed against the perineum in order to measure height of the perineum above or below the level of the ischial tuberosities. The patient can then be asked to strain and movement of the perineum from baseline can be measured.
A new device was developed which can be used in the more anatomical sitting position and allows measurement of pelvic floor both cranially, on voluntary contraction, and caudally, on straining. This consists of a tube with a balloon at one end and a magnet at the other. The balloon is placed in the rectum and inflated to hold it in place. The patient sits on a modified commode. The magnetised end of the tube sits within a cage which can measure movement of the magnet. An elastic band fixed to the floor from the magnet-end of the tube pulls the device down, so that the rectal balloon sits on the pelvic floor. Vertical movement of the magnet, and hence also the pelvic floor, is displayed on a computer, while the subject is at rest or performing various activities which involve pelvic floor movement.

The use of a barium paste enema, called a defaecating proctogram, is a radiological test of pelvic floor support. Perineal descent can be quantified this way, by measurement of the height of the anorectal angle above or below the pubococygeal line. This also allows assessment of rectovaginal septum strength and quantification of a rectocele. Dynamic MRI may be an alternative, especially in units with a wide open scanner, allowing scanning of the patient in the sitting position.

**Fatigue**

The contraction of a muscle can be measured not only at its peak, but also its response during prolonged contraction – fatigue. The measurement of whole muscle fatigue gives additional information, indicating not only the muscle strength, but also reflecting its innervation. Fatigue measurement therefore poses intriguing study questions, potentially combining the assessment of two pelvic floor components in the one measurement. If fatigue can reliably measure both muscle and nerve damage, this might be a way of quantifying the damage to the pelvic floor caused by childbirth, thereby potentially identifying those at risk of developing FI in the future, a possible screening test. This is particularly attractive because fatigue is easy to perform and is relatively non-invasive. In order to be widely introduced as a screening test, fatigue measurement would need to be both sensitive and specific, the test would have
to be acceptable to women and must be repeatable, both inter-observer and intra-individual. The physiology of skeletal muscle fatigue is discussed further in the next section.

**Fatigue**

Skeletal muscle fatigue can be defined as the “reversible decline in performance during activity”.69

Normal processes involved in producing a voluntary muscle contraction are illustrated in figure 1.1. Fatigue can occur at many points along this chain of processes. Where fatigue originates in the brain or spinal cord, e.g. loss of motivation, this is termed central fatigue. Peripheral fatigue occurs in the peripheral nerves, at the neuromuscular junction or in the muscle. Central fatigue is considered further in the Discussion.

Factors involved in peripheral fatigue are numerous and complex. Transmission of the action potential to the muscle fibre has to occur. This is the point of failure in Myasthenia gravis. During high frequency stimulation of a muscle, the force declines rapidly. This is associated with slowing and prolongation of the muscle surface action potential, indicating failure of electrical propagation.70 However, in a sustained maximal voluntary contraction, the action potential does not prolong, and it is thought that a reduction in motor neuron firing occurs, thereby maintaining force generation by avoiding the failure of electrical propagation.70

The action potential then has to be conducted through the narrow transverse tubules (t-tubules) into the centre of the muscle, reaching every fibre. The t-tubules are narrow, making fluctuations in electrolytes (extracellular K⁺ concentration and intracellular Na⁺ concentration) more likely to cause failure of action potential conduction. Changes in intracellular pH, temperature, oxygen species free radicals, glycogen, lactate, [ATP], inorganic phosphate, Mg²⁺ are all involved in the process of fatigue at the cellular level in complex, interactive manners69 – see figure 1.1. During maximal voluntary contraction, perfusion
Oxygen delivery to the muscle fibres and the effect on aerobic respiration will therefore also be important in the development of fatigue.

Skeletal muscle consists of different cell types. Type I synthesise the slow myosin isoenzyme, utilise aerobic respiration and are resistant to fatigue, whereas type II synthesise the fast myosin isoenzyme, producing a faster muscle fibre contraction velocity, utilise anaerobic respiration and are sensitive to fatigue. Type I fibres are also referred to as oxidative, as they receive their ATP supply from the oxidation of fatty acids. Type II fibres, on the other hand, obtain ATP from glycolysis, and are therefore also referred to as glycolytic. Type II fibres can be further subdivided into types IIA and IIB. Type IIA fibres can be thought of as “intermediate” in nature, having fast contraction properties but are relatively fatigue-resistant with high oxidative capacity, whereas type IIB are fatigue sensitive with very low oxidative capacity, relying on glycolysis.

One muscle fibre is innervated by one nerve. However, one nerve may innervate more than one muscle fibre. The nerve and its associated muscle fibres are termed a motor unit. A motor unit may contain very few or many muscle fibres, depending on the size of the muscle and the degree of fine control required. All the muscle fibres in one motor unit consist of the same cell type, i.e. all type I or all type II within one motor unit. Type I muscle fibres are innervated by small motor axons and type II muscle fibres are innervated by larger motor axons. Muscle contraction is initiated through recruitment of motor units. Motor units are recruited in a pre-determined order, with small motor units recruited first. These are the most excitable and contain type I, fatigue resistant muscle fibres. As increasing effort is required, more motor units of increasing size and reducing fatigue resistance are recruited. This allows fine control at lower strength contractions and the rapid increase of strength when this is required.

If whole muscle sustained contraction, whether maximum voluntary contraction or stimulated tetany, is measured over time, changes in whole muscle force generation reflect fatigue of some muscle fibres before the fatigue of others.
Therefore, where a rapid fall in contraction strength is seen after a short time, with continued contraction at a lower strength, it can be deduced that the fall in strength is as a result of fatigue of the type II muscle fibres, with persistent contraction of the fatigue-resistant type I fibres.\textsuperscript{72}

The skeletal muscles involved in the maintenance of continence include the external anal sphincter and the pelvic floor musculature. These show preponderance of type I fibres.\textsuperscript{73,74} This preponderance of type I fibres is in keeping with the continuous contraction of the pelvic floor musculature.\textsuperscript{75,76}

If muscle fibres lose their innervation they undergo changes. Atrophy of the cells occurs within months, progressing to replacement with fat and connective tissue in 1 to 2 years. However, if a muscle fibre is reinnervated within months, degenerative changes within the cell are reversible. The muscle fibre will also take on the nature of its new nerve fibre, i.e. if a fast, fatigue-sensitive fibre is reinnervated by a small motor axon, it will redifferentiate into a slow, fatigue-resistant muscle fibre.\textsuperscript{72}

The effect of changes in innervation on skeletal muscle fatigue differs, depending on the developmental stage of the muscle and length of denervation. Muscle weakness and wasting are completely reversed in adult muscles on reinnervation if this occurs within a few months,\textsuperscript{72} but denervation and reinnervation early in postnatal development in the rat results in permanent wasting and weakness.\textsuperscript{77} Fast contracting muscles are affected to a greater extent than slow-contracting muscles. Reinnervated adult fast muscles are more fatigue-resistant, with loss of fast fatigable (type IIB, glycolytic\textsuperscript{72}) fibres.\textsuperscript{77}

However, when slow muscles are chronically denervated they loose their fatigue-resistance and develop fast-fatigable properties. Shields \textit{et al} describe the loss of fatigue-resistance in human soleus muscle after chronic (> 3 years) spinal cord injury, which is not apparent after acute (< 5 weeks) injury.\textsuperscript{78}
**Figure 1.1** Skeletal muscle voluntary contraction and causes of fatigue

- **Potential for fatigue**
  - Loss of motivation
  - Failure point in Myasthenia Gravis

- **Site of action**
  - Cortex

- **Action**
  - Voluntary will
  - Activation of voltage-sensitive Ca²⁺ channels (dihydropyridine receptors, DHRPs)
  - Activation of sarcoplasmic reticulum Ca²⁺ channels (ryanodine receptors, RyR)
  - Release of Ca²⁺ from sarcoplasmic reticulum

- **Potential for fatigue (continued)**
  - Reduced by Pᵢ, ↑Mg²⁺ and ↓ATP
  - Reduced by ↑Pᵢ, ↓pH, ↑reactive oxygen species

- **Intracellular**
  - Force
  - Shortening velocity

- **Force development**
  - Reduced by ↑Pᵢ

- **Reduced by ↑ADP**

- **Loss of motivation**
  - Failure point in Myasthenia Gravis

- **Impaired conduction in the presence of raised extracellular [K⁺] and intracellular [Na⁺]**

- **Action potential**

- **Release of acetylcholine**

- **In muscle and conducted down transverse tubules (t-tubules) into the interior of muscle**

- **Neuromuscular junction**

- **Lower motor neurones of spinal cord and peripheral nerve**
EAS fatigue

As described above (see Investigation: Clinical assessment tools), anal canal manometry is a routine part of the assessment of a patient with FI. This measures the squeeze pressure generated by the anal sphincters during a momentary maximal voluntary contraction. However, assessment of the EAS may also include measurement of fatigability, by means of a sustained maximal voluntary contraction, as the faecal continence mechanism requires the delay of defecation until a socially acceptable time and place. Therefore, prolonged contraction of the voluntary musculature of the continence mechanism will be involved in this delaying of defecation. Parks stated that the maximal duration of anal sphincter contraction is “not much more than one to two minutes”. Brindley et al used an anal plug to stimulate the anal sphincters and found that they fatigue greatly during the first two minutes of a maximal tetanus, but a lower level of force can be maintained throughout the remainder of a 10 minute stimulus. In 1998, Marcello et al developed an assessment of EAS function which incorporates the fatigue rate and the maximal contraction pressure – the fatigue rate index (FRI). It is calculated as follows:

\[
\text{Fatigue rate index} = \frac{\text{Squeeze pressure} \ (\text{measurement of pressure})}{\text{minutes}} - \frac{\text{Fatigue rate} \ (\text{measurement of pressure/min})}{\text{minutes}}
\]

The FRI is measured in minutes. It can therefore be compared between laboratories using different measures of pressure (e.g. cmH_2O or mmHg). The inclusion of both squeeze pressure and fatigue rate is important, as one who can generate greater pressures will maintain a useful closing pressure for longer than another whose EAS fatigues at the same rate but cannot generate the same squeeze pressure. The FRI was found to differ significantly between continent controls and patients with FI.

This alteration in fatigue may be as a result of alteration in the cell type ratio of the EAS. In 1977, Parks described grouping of fibre types within the EAS and, to a lesser extent, other striated muscles of the pelvic floor. These histological changes were consistent with denervation and subsequent reinnervation of the EAS. Where ingrowing nerve axons reinnervate a
denervated muscle, they will tend to reinnervate the muscle fibres within close proximity to the nerve axon, rather than the mosaic pattern of intermixed type I and II fibres usually seen in biopsies of healthy muscle. This gives the appearances of fibre type grouping, described by Parks.\textsuperscript{51} If fatigue sensitive, fast-twitch fibres, with their ability to produce greater force, were selectively lost as a result of an insult (i.e. vaginal delivery), with selective preservation of slow-twitch fibres, the EAS would not be able to produce as much force (reduced squeeze pressure) but would be able to resist fatigue. Results of fibre type analysis from anal sphincter biopsies in controls and FI patients are currently awaited in this group.

**Pelvic floor fatigue**

Global pelvic floor function can be measured by means of EMG,\textsuperscript{15} by ultrasound measurement of bladder neck movement,\textsuperscript{82} or by pressure measurement via a vaginal probe.\textsuperscript{76} Some studies have shown differences in pelvic floor function in urinary incontinence\textsuperscript{76} and post partum.\textsuperscript{33} However, the few studies that have looked at fatigability of the pelvic floor have not found a significant effect. Verelst and Leiveth\textsuperscript{76} showed a reduction in force of pelvic floor contraction when corrected for body weight, as measured by a vaginal strain gauge, in patients with urinary incontinence compared with controls. They did not show any statistically significant difference in time to fatigue between the two groups. Peschers et al\textsuperscript{62} found no effect of fatiguing activities (coughing and maximal pelvic floor contractions) on bladder neck mobility measured by transabdominal ultrasound in nulliparous volunteers. Only one study has looked at the presence of fatigability of the pelvic floor musculature in patients with FI.\textsuperscript{83} This used an adjustable metal frame, held fixed in relation to the bony pelvis, and pelvic floor function was assessed by use of an intrarectal balloon. They report reduced pressure generation by levator ani in incontinent patients but no difference in response to fatigue between continent and incontinent subjects.
Pelvimetry

FI is more common after vaginal delivery of large babies and instrumental delivery, especially forceps delivery.\(^2\) Women who have only ever delivered by Caesarean section appear to be protected from the development of faecal and urinary incontinence.\(^8^4\) If pelvic floor damage is more common after the vaginal delivery of large babies, it would seem logical that cephalopelvic disproportion (CPD) is more likely to cause pelvic floor damage, damage to the innervation of the pelvic floor, and resultant FI, than purely large babies. It would seem logical and simple that elective Caesarean section would prevent pelvic floor damage and subsequent FI, especially as impairment of pelvic floor innervation is not seen in women post elective Caesarean section.\(^1^5\) Unfortunately, the situation may not be that simple. A systematic review concluded that Caesarean section does not prevent the development of FI in the short term (maximum of six years follow up).\(^8^5\) However, as the prevalence of FI increases with age\(^8^6\) and is more common after the menopause\(^8^7\), it may be that follow up was inadequate. A 34-year follow up study found a long term protective effect of Caesarean section for FI and urinary incontinence,\(^8^4\) but this study only included 6 women delivered solely by Caesarean section. A separate study of the prevalence of pelvic floor disorders calculated that seven women would have to be delivered purely by Caesarean section in order to prevent a pelvic floor disorder in one woman.\(^8^8\) There are also concerns about maternal and fetal morbidity and mortality associated with Caesarean section.\(^8^9\) Despite these issues, increasing our understanding of the relationship between vaginal delivery, fetal head size and anal function will aid our counselling of patients, especially those who have had a difficult previous delivery, perhaps complicated by third degree perineal tear, and wish to discuss delivery options.

Assessment of CPD is achieved by means of pelvimetry – the measurement of pelvic diameters. This can be done clinically, by means of a bimanual pelvic examination, or radiologically, by means of X-ray, CT or MRI. Radiological assessments of pelvimetry are felt to be more accurate than clinical assessments. More recently, ultrasound has been developed as an assessment of pelvimetry. This is an imaging technique which can be safely
used during pregnancy. Japanese researchers have shown that the obstetric conjugate, the distance from the posterosuperior border of the symphysis pubis to the sacral promontory, can be measured by means of ultrasound.\cite{90} This ultrasonographic obstetric conjugate correlates with radiographic conjugate (measured on plain X-ray).

Pelvimetry, whether assessed clinically\cite{91} or radiologically,\cite{92} has been found not to affect the obstetric decision making, as most women are offered a trial of labour, irrespective of the outcome of pelvimetry measurements.\cite{91,93} However, pelvimetry in this situation is used to assess whether it is possible for the fetus to be delivered vaginally, not as an estimation of the degree of pelvic floor damage which may occur as a result of vaginal delivery. If a correlation between CPD and the development of FI (studied retrospectively) or perineal damage (studied prospectively) can be found, then pelvimetry may be found to be a useful tool to inform decision making.

**Summary and aims**

So far I have argued from the evidence that childbirth can result in faecal incontinence, whether this is immediate or some years post partum. Childbirth, especially vaginal delivery, results in measurable changes in the anal sphincter muscles, pelvic floor musculature, their innervation, and in the connective tissue support. Changes are more pronounced after a difficult vaginal delivery, but may also be found as a result of labour alone.

Skeletal muscle fatigue measurement gives an assessment of not only muscle strength, but also will alter with both muscle damage and loss of innervation. Fatigue of the EAS has been shown to differ between continent and incontinent subjects. This single measurement may, therefore, be a useful assessment of global pelvic floor damage post partum.

Studies of FI have mainly concentrated on measurement of anal sphincter function. However, vaginal delivery causes stretching of the entire pelvic floor musculature, which is also important in the maintenance of continence.
Measurement of pelvic floor muscle fatigue may therefore be a more useful assessment of global pelvic floor damage.

Faecal incontinence does not develop in every woman who delivers vaginally. It may be that childbirth is the initial insult in a susceptible woman, who develops FI after sustaining further insults to her pelvic floor. If it were possible to predict who would develop FI as a result of childbirth, this raises the possibility of preventing the development of symptoms in some women by discussing alternative delivery options. Since difficult childbirth and the delivery of large babies cause more changes in the pelvic floor, it may be that measuring maternal pelvis size (pelvimetry) and comparing this with fetal head size could be useful in predicting increased pelvic floor trauma.

This thesis therefore aims to answer the following:

- Does childbirth alter anal fatigue rate?
- Does pelvic floor muscle fatigue differ between continent and incontinent women? Does childbirth alter pelvic floor fatigue?
- Does the route of delivery affect changes in anal or pelvic floor fatigue?
- Can maternal pelvis size be measured accurately and safely in pregnancy and does this relate to measured differences in pelvic floor function post partum?

These aims are addressed in a series of experiments:

- Measurement of anal manometry and fatigue during pregnancy and after delivery (Chapter 4)
- Comparison of pelvic floor strength and fatigue between continent and incontinent women (Chapter 5).
- Measurement of pelvic floor strength and fatigue during pregnancy and after delivery (Chapter 5).
- Measurement of ultrasound pelvimetry and comparison with changes in anal manometry and fatigue and pelvic floor strength and fatigue pre and post delivery (Chapter 6).
In all of these experiments, reliable, reproducible tests must be used, so that any changes in the pelvic floor structures which are measured, can be confidently assigned to the insult under investigation, rather than measurement error. Reproducibility experiments are therefore discussed in Chapter 3.
2. Methods
This chapter initially describes the experimental techniques used in this thesis. It then describes the studies including these techniques and the justification behind each.

**Techniques**

**Manometry**

Anal manometry was measured by means of a water filled micro-balloon (Precision Dippings, Bristol, construction expanded in Appendix 1), connected via non-distensile tubing to a pressure transducer, amplifier box (University Hospital of South Manchester medical engineering department), and cable to a PC card in a laptop. Data were recorded by means of software designed by the University Hospital of South Manchester medical engineering department at a rate of 30 data points per second and transferred to Excel (Microsoft, USA) for analysis.\textsuperscript{94}

The calibration of the manometry equipment was checked against a known pressure of 0, 50, 100, 150 and 200 cmH\textsubscript{2}O for 5 seconds in increasing and decreasing pressure steps. Where drift from true pressure was recorded, this was corrected by adjusting the gain and offset within the amplifier box.

After obtaining consent, participants were positioned in the left lateral position with the anus exposed. The pressure was zeroed with the micro-balloon held level with the anal verge. The lubricated micro-balloon was then inserted to 5 cm from the anal verge and pressure allowed to settle before recording resting pressure. The participant was then asked to voluntarily contract the anal canal (“I would like you to squeeze your bottom as though you are trying to keep something in.”) and squeeze pressure is recorded. Recordings of resting and squeeze pressure are repeated at 4, 3, 2 and 1 cm from the anal verge. Maximum resting pressure of the anal canal was calculated by subtracting rectal pressure (usually resting pressure at 5 cm from the anal verge) from the highest resting pressure recorded. Maximum squeeze pressure was defined as the greatest rise in pressure from resting pressure.
Fatigability of external anal sphincter

Fatigue of the external anal sphincter (EAS) was measured using the manometry equipment immediately after measuring anal canal pressures. The micro-balloon was positioned at the point in the anal canal where the greatest pressure rise was obtained – maximum squeeze pressure. Fatigue was recorded during a voluntary anal contraction, maintained for 22 seconds. After a two minute rest period, the fatigue measurement was repeated.

The fatigue rate of the EAS was analysed in Excel. Figure 2.1 summarises the fatigue rates calculated. The rise in pressure at the beginning of the prolonged squeeze, the time of the maximum pressure and the time of the lowest pressure after the first fall in pressure were noted.

**Figure 2.1** Example of fatigue measurement. Anal canal pressure is recorded in cmH₂O per data point.

The following fatigue rates were then calculated:

- **Overall fatigue rate**: rate of fall in pressure over 20 seconds from maximum pressure generated.
- **Type II fatigue rate**: rate of fall in pressure from maximum pressure to the lowest pressure in the first downwards trend.
• Type I fatigue rate: rate of fall in pressure after the first downwards trend.

Fatigue rates were obtained by using Excel to place a linear best fit line on the graph. The equation of the graph gives the slope and intersection with the y axis in the form:

\[ y = mx + c \]

where:

- \( m \) = slope of the graph
- \( c \) = point of intersection with the y axis

The slope (\( m \)) is given in cmH\(_2\)O per data point. Data were collected at a rate of 30 per second or 1800 per minute. In order to convert this to cmH\(_2\)O per minute, the slope was multiplied by 1800.

Fatigue rate index, a measure of EAS function which incorporates fatigue rate and maximal voluntary contraction suggested by Marcello et al.,\(^{80}\) was calculated as follows:

\[
\text{Fatigue rate index} = \frac{\text{Squeeze pressure (cmH}_2\text{O)}}{\text{(minutes)}} - \frac{\text{Fatigue rate (cmH}_2\text{O/min)}}
\]

The area under the fatigue measurement curve was also calculated for each fatigue measurement. Essentially, the area was calculated by adding the pressure generated above resting pressure for each data point. Initially, the resting pressure was calculated in order to subtract this value from the pressure recording at each time point. The resting pressure was seen to fall after maintaining a maximal voluntary contraction for 20 seconds in some study subjects. The resting pressure in the anal canal is known to vary, due to the presence of slow waves and ultra slow waves generated by the IAS.\(^{95}\) Resting pressure cannot be measured simultaneously with squeeze pressure, so the activity of the IAS during the maintained squeeze cannot therefore be known. The difference in resting pressure before and after a maintained voluntary contraction could have been ignored, by subtracting only the resting pressure at the start of the contraction from each data point. However, it was felt that this would produce an area reading much lower than the true activity of the EAS.
Therefore, a reducing value of resting pressure was subtracted from the squeeze pressure at each time point, in order to avoid artificially reducing the area under the curve. The gradient of a line joining resting pressure at the start and end of the fatigue measurement was calculated from inserting the co-ordinates of known points along this line into the formula of a straight line, \( y = mx + c \), as above, and using simultaneous equations to calculate \( m \) and \( c \). The value of \( y \) for each time point \( (x) \) was subtracted from the measured pressure. In some subjects, no resting pressure fall was seen, so the value of the initial resting pressure was subtracted from the measured pressure at every time point. Those calculated squeeze pressures with a positive value were then added for each time point from the commencement of the rise in pressure to 20 seconds (600 data points) beyond the maximal pressure generated, to give the area under the curve (in a random unit of measurement). A worked example of this calculation of area under the curve is given in appendix 2.

Given the high degree of intra-individual variability in EAS fatigue measurements (see Chapter 3: Reproducibility), univariate analysis of variance was used to compare fatigue rates between groups or between time points. A simpler statistical method would have been to calculate the mean of the two measurements of fatigue at each time period for each participant, then use a t-test to assess any statistical difference. However, this would reduce the variability within the group at each time point, giving artificially strong power to the statistical calculations (type I statistical error).

**Fatigability of the pelvic floor musculature**

A new technique for measuring the strength and resistance to fatigue of the pelvic floor musculature was developed using commercially available equipment, designed for use by physiotherapists, assessing and training patients in the use of pelvic floor exercises.

Pelvic floor strength was measured by means of a blue-tooth enabled Peritron (Cardio Design, Australia), connected via air-filled tubing to a vaginal probe. With the patient in the left lateral position, the vaginal probe was covered with a
condom and placed in the vagina with the pressure-sensitive zone straddling the pelvic floor musculature. A correct pelvic floor contraction was confirmed by a visible cranial movement of the vaginal probe, associated with a rise in vaginal pressure. The Peritron was zeroed before commencement of recordings. Participants were asked to generate a maximal pelvic floor contraction, to relax, then to hold a maximal contraction for 20 seconds. These brief and maintained squeezes were repeated after a 2 minute rest period. Pressure measurements were taken at a rate of 10 per second, using PhysioLog Pro software (PhysioLog Products, Pty Ltd, Australia), and analysed using Excel (Microsoft, Redmond, Washington, USA). Maximal squeeze pressure was documented as the best pressure generated, out of the four contractions carried out. Fatigue rate was calculated by applying a best-fit linear graph for the period from the maximum pressure generated to 20 seconds later and multiplying the gradient by 600 (number of data points in 1 minute).

Again, the use of multiple measurements with high degree of variability (see Chapter 3: Reproducibility) necessitated the use of univariate analysis of variance to compare pelvic floor fatigue rates between groups or between time points.

**Symptom severity scoring**

Various validated symptom severity scores are in use for the assessment of faecal incontinence. The Vaizey score has been used consistently in this department for many years. It is illustrated in table 2.1. Quality of life is also an important issue in the treatment of this benign but debilitating condition. The Manchester Health Questionnaire (MHQ) is a symptom-specific, health related quality of life questionnaire developed in 2001 for the specific assessment of quality of life in this patient group. Values for the domains general health, impact of FI, role, physical, social, personal, emotions, sleep and severity are obtained and summed to give a value for FI-specific quality of life between 0 and 900.
<table>
<thead>
<tr>
<th></th>
<th>Never</th>
<th>Rarely (one episode per month)</th>
<th>Sometimes (more than once a month but less than weekly)</th>
<th>Weekly</th>
<th>Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you ever leak solid stools?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Do you ever leak liquid stools but hold onto solid stools?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Do you ever leak gas but hold onto solid and liquid stools?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>How often does your bowel leakage problem affect your lifestyle?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Do you need to wear a pad or plug?</td>
<td>No</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>No you need to take constipating medicines to make your stools firmer and more controllable?</td>
<td>0</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If you had the urge to open your bowels would you have had an accident if you could not reach a toilet within 15 minutes?</td>
<td>0</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 The Vaizey score of faecal incontinence, with scores for each item inserted in boxes. The score is obtained by adding the values for each tick. The possible scores range from 0 to 24.

Ultrasound pelvimetry

The anteroposterior diameter of the pelvis was measured using transabdominal ultrasound scanning from a technique described by Katanosaka et al.\textsuperscript{90} Using a 3.5 MHz probe, the upper border of the symphysis pubis was identified as a bright echo with acoustic shadow behind. The posterior edge of this bright echo was used as the start of the measurement. The sacrum was identified as the last identifiable bright echo in the depth of field, illustrated in figure 2.2. The most caudal part of this bright echo was taken as the end of the measurement. All measurements were taken by one senior ultrasonographer. To ensure that the echoes identified on ultrasound corresponded correctly with the bony landmarks, the ultrasound obstetric conjugate was compared with that measured on magnetic resonance imaging in women undergoing MRI pelvis for other clinical reasons who agreed to undergo ultrasound pelvimetry as well.
Figure 2.2 Example of ultrasound pelvimetry (a), showing bladder (B), symphysis pubis (SP), and sacrum (Sa). The measured pelvis size was compared with that measured on magnetic resonance imaging (b).

Studies

Changes in the pelvic floor during pregnancy and after delivery in primigravid women

This observational study measured anal and pelvic floor parameters during pregnancy and after delivery in primigravid women. Ethical approval was obtained. Women booking for antenatal care at Withington Community Hospital or Wythenshawe Hospital for their first pregnancy were approached to participate. Written information was provided either by post or personally. Potential participants were given several days to consider participation and followed up by phone for a decision.

Anal manometry, EAS fatigue, pelvic floor strength and fatigue were measured using the techniques described above at or close after booking, between 36 and 40 weeks gestation and again 4 months post partum, in order to measure any potential changes as a result of the pregnant state or secondary to delivery. Due to low recruitment rates, a number of women were recruited from their 20 week anomaly ultrasound scan. These women had only one set of measurements taken during pregnancy. Information regarding labour and
delivery was also collected, listed in figure 2.3. Ultrasound pelvimetry was measured in a number of the participants.

**Pelvic floor fatigue**

Pelvic floor strength and fatigue were compared between women with normal bowel control and faecally incontinent women. Ethical approval for the study was granted by the Cumbria and Lancashire A Research Ethics Committee. Asymptomatic subjects were recruited from women admitted to the general surgical wards for unrelated surgical procedures. Data from primigravid women were also included in the asymptomatic group. Incontinent subjects were recruited from among women admitted for sacral nerve stimulator implantation. The technique described above was used to measure pelvic floor strength and fatigue. Women also underwent measurement of anal manometry and EAS fatigue, in order to compare strength and fatigue of pelvic floor and EAS musculature. Age and parity were also documented for each participant.
## Delivery data – please enter:

<table>
<thead>
<tr>
<th>Onset of labour (please tick any that apply)</th>
<th>spontaneous</th>
<th>induced</th>
<th>prostin</th>
<th>rupture of membranes</th>
<th>syntocinon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of stages of labour (minutes)</td>
<td>1\textsuperscript{st}</td>
<td>2\textsuperscript{nd}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivery (please tick)</td>
<td>SVD</td>
<td>Ventouse</td>
<td>Forceps</td>
<td>Elective Caesarean section</td>
<td>Emergency Caesarean section</td>
</tr>
<tr>
<td>Perineum (please tick)</td>
<td>Intact</td>
<td>Episiotomy</td>
<td>1\textsuperscript{st} degree tear</td>
<td>2\textsuperscript{nd} degree tear</td>
<td>3\textsuperscript{rd} degree tear</td>
</tr>
</tbody>
</table>

## Baby details – please enter:

<table>
<thead>
<tr>
<th>Birth weight (grams)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Head circumference (cm)</td>
<td></td>
</tr>
<tr>
<td>Gestation (weeks+days)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.3** Labour, delivery and baby details collected per participant.
3. Reproducibility
A test or measure of physiological function is only useful if it can reliably and repeatedly offer the same results when conditions are unchanged. This chapter studies the repeatability of the important tests used in this thesis, thereby allowing conclusions to be drawn about the results of the studies using these tests.

**Anal manometry and fatigue**

The repeatability of anorectal physiology studies have been studied previously, looking at inter-observer\(^99\) and intra-observer\(^100\) repeatability and within-subject variability.\(^55\) Although some tests of the anorectum have good repeatability (e.g. sphincter length, PNTML), manometry tends to be highly variable. Both maximum resting pressure (MRP) and maximum squeeze pressure (MSP) of the anal canal vary considerably between tests. The bias in both inter- and intra-observer repeatability studies was low for both MRP and MSP, suggesting that tests are repeatable, but standard deviation was high, indicating a high degree of intra-individual variability. Reasons for this may include the presence of slow waves and ultraslow waves causing variation in the MRP,\(^55\) and differences in participant co-operation contributing to variable MSP.\(^99\) Differences in technique between investigators are unlikely to be the cause of the variability, because of the low bias. If MSP is highly variable because of changing participant co-operation, where only a short voluntary contraction is required, it is likely that fatigue rate will be more variable, as a sustained voluntary contraction is required. This section aims to quantify the degree of variability in EAS fatigue rate.

**Method**

The method of measuring anal manometry and fatigue is described fully in chapter 2. Using a water-filled microballoon, resting and squeeze tone are measured at one centimetre intervals for 5 cm from the anal verge. Maximum resting pressure (MRP) is calculated by subtracting rectal pressure from the maximum resting tone recorded. Maximum squeeze pressure (MSP) is the maximum increment above resting tone achieved on voluntary contraction.
Fatigue of the external anal sphincter (EAS) is measured during a 20 second sustained voluntary contraction, and analysed in Excel (Microsoft, USA) to give the gradient of the slope, or fatigue rate (FR). Fatigue rate index (FRI) is an estimate of the length of time that an individual can sustain a voluntary contraction and is calculated by dividing the squeeze pressure by the negative of the fatigue rate. Participants were routinely asked to repeat the sustained contraction, thereby giving two measures of FR (FR1 and FR2) every time they participated in a study. This ensured that at least one FR was measured if a technical problem with the equipment was encountered, and also allowed the repeatability of FR to be assessed.

The fatigue rate of the EAS was measured in subjects recruited to both the study measuring changes in the pelvic floor as a result of pregnancy and delivery and the comparison between continent and incontinent subjects. This analysis of FR repeatability therefore includes 97 subjects. The two measures of FR from only the first time a participant was measured are included in this analysis of repeatability. Some participants in the studies underwent anal manometry and fatigue measurement only once, whereas others underwent the measurements more than once. Including all measurements of anal fatigue in the statistical analysis would therefore include some individuals once and some two or three times, thereby skewing the results of the repeatability analysis. Therefore only first FR measurements are included.

A Pearson correlation was used to show the degree of correlation between the repeated FR measures. A paired t-test was used to determine if the repeated FR measures were statistically significantly different. A Bland Altman plot was used to show the degree of agreement between the repeated measures.

**Results**

A typical graph of pressure over time is shown in figure 3.1. Typically, a sharp rise in pressure is seen, when the participant is asked to start squeezing. This is followed by a steep fall in pressure, then a slower fall in pressure. The first
steep fall is termed type II fatigue rate and the second, slower fall is termed type I fatigue rate.

**Figure 3.1** Typical trace of EAS fatigue measurement. Anal canal pressure is recorded in cmH$_2$O over a 20 second squeeze and plotted against time in data points (at a rate of 30 per second).

**Fatigue repeatability**

The mean FR1 was -66.91 (± standard deviation, 83.99) cmH$_2$O/min and the mean FR2 was -56.98 ± 63.65 cmH$_2$O/min. The two measurements of fatigue rate, FR1 and FR2, correlate significantly (Pearson correlation, $r = 0.630$, $p < 0.001$) and there is no statistically significant difference between them on paired t-test. However, to give a better understanding of the degree of agreement between the two measures, a Bland Altman plot of mean of both fatigue rates against the difference between the fatigue rates was charted, shown in figure 3.2. This method allows the graphical representation of the degree of
agreement between two measurements. The bias is calculated as the mean of the differences between the two measurements and should be close to zero. If it is not, this reveals that one of the tests consistently records higher results than the other. If there is close agreement between two measurements, the individuals in the scatter plot will lie close to the mean. The degree of agreement between two measurements can be quantified as follows: the repeatability co-efficient is twice the standard deviation of the difference between the two measurements, 95% of individuals will lie between the mean ± repeatability co-efficient. From figure 3.2 it can be seen that the bias was -7.66 cmH\textsubscript{2}O/min and the repeatability co-efficient was 127.83 cmH\textsubscript{2}O/min for repeated overall fatigue rate measurements.

![Bland Altman plot](image)

**Figure 3.2** Bland Altman plot of mean of repeated fatigue measurements against the difference between repeated fatigue rates, including reference lines of mean (bias) and mean ± twice standard deviation.
Repeatability of types II and I fatigue rates were also calculated. The mean, standard deviation, bias and repeatability co-efficient for types II and I fatigue rates are shown in table 3.1. The repeatability of fatigue rates of continent and incontinent subjects were analysed separately and are shown in table 3.2.

<table>
<thead>
<tr>
<th></th>
<th>Mean 1st</th>
<th>Standard deviation 1st</th>
<th>Bias 1st</th>
<th>Repeatability co-efficient 1st</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type II</td>
<td>-1234.65</td>
<td>1192.44</td>
<td>-91.32</td>
<td>2208.26</td>
</tr>
<tr>
<td></td>
<td>-1130.35</td>
<td>1197.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>-37.19</td>
<td>70.36</td>
<td>-12.28</td>
<td>131.87</td>
</tr>
<tr>
<td></td>
<td>-22.39</td>
<td>63.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.1** Mean, standard deviation of 1st and 2nd type II and I fatigue rates and bias and repeatability co-efficient for repeated type I and II fatigue rates. All values in cmH$_2$O/min.

<table>
<thead>
<tr>
<th></th>
<th>Continent (n = 46)</th>
<th>Incontinent (n = 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR1</td>
<td>-104.91 ± 95.33</td>
<td>-22.59 ± 33.28</td>
</tr>
<tr>
<td>FR2</td>
<td>-82.90 ± 69.18</td>
<td>-23.14 ± 33.48</td>
</tr>
<tr>
<td>Bias</td>
<td>-12.5</td>
<td>-1.11</td>
</tr>
<tr>
<td>Repeatability co-efficient</td>
<td>160.64</td>
<td>60.14</td>
</tr>
</tbody>
</table>

**Table 3.2** Mean ± standard deviation of 1$^{st}$ and 2$^{nd}$ fatigue measurements (FR1 and FR2 respectively) for continent and incontinent subjects, with bias and repeatability co-efficient for repeated fatigue measurements calculated separately for continent and incontinent groups. All values in cmH$_2$O/min.

When the repeatability of the fatigue rate index (FRI) was analysed, the bias was 1.04 minutes and repeatability co-efficient was 20.14 minutes. For continent subjects only, the bias was -0.80 minutes and repeatability co-efficient was 6.1 minutes, while for incontinent subjects only, the bias was 3.52 minutes and the repeatability co-efficient was 29.47 minutes.

**Positive fatigue rates**

A number of subjects produced a positive fatigue rate, i.e. the pressure rose with time during a sustained voluntary contraction, rather than falling. An example is given in figure 3.3. In 93 subjects who had analysable fatigue measurements, 71 produced only negative fatigue rates, 10 produced only
positive fatigue rates and 12 produced one negative and one positive. Of 175 fatigue measurements, 29 (17%) were positive. Incontinent subjects were more likely to have positive fatigue rates than continent subjects (chi squared, p = 0.025).

![EAS fatigue measurement](image)

**Figure 3.3** Example of positive fatigue rate curve, with sustained anal canal voluntary contraction against time.

**Area under the fatigue curve repeatability**

The area under the fatigue curve (AuC) was calculated as described in Chapter 2: Methods and in Appendix 2. It is measured in a random unit. The mean (± standard deviation) of the area under the curve of the first fatigue measurement (AuC1) was 16749 (± 16556) and for the second (AuC2) was 14963 (± 13983).
First and second AuC calculations correlate strongly and significantly (Pearson correlation, $r = 0.818$, $p < 0.001$). AuC was calculated for two fatigue measurements in 80 subjects. The bias of repeated AuC was 1786 and the repeatability co-efficient was 19048.

The AuC for continent and incontinent subjects are shown in table 3.3, as are the bias and repeatability for AuC when analysed for continent and incontinent groups separately. AuC was compared between continent and incontinent subjects and both AuC1 and AuC2 were found to be highly significantly different (paired t-test, $p < 0.001$). When both measures of AuC were compared between continent and incontinent groups in one analysis of variance, there was still a highly significant difference ($p < 0.001$).

<table>
<thead>
<tr>
<th></th>
<th>Continent (n = 46)</th>
<th>Incontinent (n = 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuC1</td>
<td>23331 ± 18726</td>
<td>7816 ± 7013</td>
</tr>
<tr>
<td>AuC2</td>
<td>19929 ± 15338</td>
<td>7978 ± 7359</td>
</tr>
<tr>
<td>Bias</td>
<td>2811</td>
<td>399</td>
</tr>
<tr>
<td>Repeatability co-efficient</td>
<td>24382</td>
<td>6643</td>
</tr>
</tbody>
</table>

**Table 3.3** Mean ± standard deviation for 1$^{st}$ and 2$^{nd}$ measures of the area under the fatigue curve (AuC1 and AuC2 respectively), plus bias and repeatability co-efficient of repeated AuC measures. Random units.

**Discussion**

The anal fatigue rate was found to be highly variable, with a repeatability co-efficient of 127.83 cmH$_2$O/min. This is a clinically significant difference: if the mean fatigue rate in continent subjects was -104.91 cmH$_2$O/min and -22.59 cmH$_2$O/min in incontinent subjects, this difference is only around 80 cmH$_2$O/min, much lower than the repeatability co-efficient of 128 cmH$_2$O/min. However, the bias of repeated fatigue rate measurements is low, indicating good test-retest repeatability. The high repeatability co-efficient was expected given the known intra-individual variability of MSP. However, MSP is still used, both clinically and for research purposes, despite its high degree of variability, giving useful information about individuals and patient groups. Therefore, FR can still be regarded as useful in clinical or research practice, as long as its large variability is borne in mind, since differences in the fatigability of the anal
canal have been found between patient groups.\textsuperscript{80,81} The bias and repeatability co-efficient are lower for incontinent subjects. Although it is possible that fatigability is more repeatable in incontinent subjects, it is more likely that this is because the fatigue rates are lower, therefore the range of measurements is smaller, making standard deviation smaller and consequently reducing the repeatability co-efficient, which is calculated from the standard deviation.

Seventeen percent of fatigue rates measured are positive, i.e. the pressure rises with time, rather than falling as is expected. This compares with 25% of fatigue rates in previous work.\textsuperscript{102} In some, the positive fatigue rate is a feature of a wandering baseline and in others it is due to the patient straining rather than squeezing, as illustrated in figure 3.4. However, in others the pressure rises as expected on commencing the sustained voluntary contraction, falls rapidly (type II fatigue rate) then starts to rise again throughout the remainder of the sustained contraction, rather than falling as expected (see figure 3.3).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3_4.png}
\caption{Examples of positive fatigue rates: (a) in this measure of EAS fatigability is due to lack of sustained contraction and a wandering baseline, rather than a true rise in pressure from ongoing, increasing EAS contraction, while in (b) the pressure trace is of a sustained strain pattern rather than voluntary contraction.}
\end{figure}
It is possible that motor unit recruitment accounts for this pattern: rather than all motor units being recruited at the start of the contraction, it may be that more are recruited as the contraction is sustained. This may be due to the subjects not following the instructions correctly, not trying to maintain a maximal contraction throughout the 20 second period, but rather contract sub-maximally in order to allow themselves to sustain the contraction rather than fatiguing. Whether this is a feature of central control or peripheral motor unit recruitment cannot be determined in this study. It would require EMG analysis of the contraction to analyse motor unit recruitment further.

Use of the area under the fatigue curve has not been reported in the investigation of FI before. We have found that it differs significantly between continent and incontinent subjects. It is highly variable, which again is unsurprising given the high variability of both MSP and FR, both of which AuC reflects. As seen with FR, the variability if AuC is lower in incontinent subjects, but again this may be the result of lower AuC measurements in incontinent subjects, with a smaller range, resulting in a lower variability.

**Pelvic floor strength and fatigue**

A wide range of different methods have been used to assess pelvic floor muscle (PFM) contraction. Assessment methods either quantify the PFM strength or show whether a subject is able to correctly contract their PFM voluntarily. Methods of assessing PFM strength include transvaginal palpation of the muscles, manometric assessment of pressure generated within the vagina and use of strain-gauges to measure force generation (dynamometers).  

A variety of methods for quantifying the clinical assessment of PFM strength have been described, from description of four parameters of PFM contraction, each on a three-point scale,\textsuperscript{103} to quantification of the contraction strength alone on a scale of 0 to 5,\textsuperscript{104-106} or more complex assessments.\textsuperscript{107} Test-retest reliability of clinical assessment has been shown to be good, with agreement of 100\% for assessment of strength of contraction on a 3 point scale,\textsuperscript{103} but inter-
observer repeatability is only fair, with correlation coefficients of 0.6 to 0.7. Inter-observer repeatability can be improved with education of the observers.

Quantification of the PFM strength can be undertaken with manometry devices, measuring pressure generated by the PFM, usually acting around the vagina, because the other two channels which cross the pelvic floor have dedicated sphincter complexes increasing pressure within the channel, not just the effect of the PFM. Manometry devices vary. They measure pressure in different units, the size of the probe varies, altering distraction of the muscles and thereby altering biomechanics of the muscle, and different probe materials and contents will transmit pressure generation differently. Therefore, results from one device cannot be compared with results from another. However, reliability testing of one technique should be transferable to another study using the same technique but different manometry device. One study of an air-filled vaginal probe used to measure PFM contractions found median intra-individual variation of 8.5 cmH\textsubscript{2}O (95% confidence interval 5.5 to 20 cmH\textsubscript{2}O). Other studies comparing clinical examination with manometry devices have found conflicting results, with some showing significant correlation between clinical examination and manometric assessment of PFM strength and others showing no difference in maximal vaginal squeeze pressure between women grouped as having “weak”, “moderate”, “good” or “strong” PFM strength on vaginal palpation.

Dynamometers measure force generation by means of strain-gauges. These can be placed vaginally or rectally. Assessment of a perineal dynamometer measuring traction of levator ani on an intrarectal balloon stabilised against the bony pelvis, found high reproducibility of levator ani contraction (intraindividual coefficient of variation of 4.6% ± 1.1%). Reproducibility of fatigue measurements were not studied.

As with anal MSP, pelvic floor strength is likely to be highly variable, given the voluntary co-operation required. If pelvic floor strength is variable, fatigue rate is likely to be more variable. This section aims to quantify the degree of variability in pelvic floor strength and fatigue.
Method

The method of measuring pelvic floor strength and fatigue are fully described in Chapter 2. Briefly, with the participant in the left lateral position, a covered, lubricated air-filled probe, connected to a Peritron (Cardio Design, Australia), is inserted into the vagina with the compliant part of the probe straddling the pelvic floor muscles. The participant is asked to perform a maximal pelvic floor contraction and correct technique is ensured by visualising a cranial movement of the probe coinciding with a rise in pressure recorded by the Peritron. The Peritron is zeroed and the recording software on the laptop (PhysioLog Pro, PhysioLog Products, Pty Ltd, Australia) is commenced before asking the participant to perform a maximal pelvic floor contraction, relax, then sustain a pelvic floor contraction for 20 seconds. These contractions are repeated after a 2 minute rest period.

Pelvic floor strength and fatigue were measured in subjects recruited to both the study measuring changes in the pelvic floor as a result of pregnancy and delivery and the comparison between continent and incontinent subjects. This analysis of pelvic floor strength and fatigability therefore includes 85 subjects, 39 incontinent women and 46 continent women. Where subjects underwent more than one measurement of pelvic floor strength and fatigue, only the first set of readings are included, to avoid introducing bias caused by the inclusion of some subjects once and others more than once in the analysis.

Pearson correlation was used to show the degree of correlation between repeated measures, paired t-test used to determine any statistically significant difference between repeated measures, and Bland Altman plot used to show the degree of agreement between repeated measures.

Results

A typical graph of pressure over time during a short then a sustained maximal voluntary pelvic floor contraction is shown in figure 3.5. Typically, the pressure
is maintained better by the pelvic floor muscles, than the EAS, reflected in less of a steep initial fall in pressure (type II fatigue rate) and little if any fall in pressure thereafter (type I fatigue rate).

![Pelvic floor squeeze pressure and fatigue graph](image)

**Figure 3.5** Typical trace of pelvic floor maximal contraction, relaxation, then sustained maximal contraction over 20 seconds. Pressure is measured in cmH$_2$O and is plotted against time in data points (at a rate of 10 per second).

**Maximum squeeze pressure repeatability**

The maximum pelvic floor squeeze pressure was defined as the maximum of all four squeezes produced at one session and in the whole subject group had a median of 13 cmH$_2$O (range 0 – 75 cmH$_2$O). In order to examine the repeatability of pelvic floor squeeze pressure, the two recorded short pelvic floor contractions (VMSP1 and VMSP2) were compared. The median VMSP1 for the whole group was 15 (range 1-71) cmH$_2$O and VMSP2 was 14 (1 – 75) cmH$_2$O. These correlated strongly and significantly (Spearman correlation, r = 0.952, p < 0.001). The degree of agreement between repeated pelvic floor contractions is illustrated in figure 3.6, which shows that the bias was 2.18 cmH$_2$O and the repeatability co-efficient was 10.34 cmH$_2$O.
**Figure 3.6** Bland Altman plot of mean of repeated pelvic floor contractions against difference between repeated pelvic floor contractions, illustrating the degree of agreement between the two measurements.

**Fatigue rate repeatability**

The mean 1st fatigue rate (VFR1) was -12.04 cmH\textsubscript{2}O/min (± standard deviation 18.50 cmH\textsubscript{2}O/min) and for the 2nd (VFR2) was -9.81 (± 15.54) cmH\textsubscript{2}O/min. These correlated strongly and significantly (Pearson correlation, r = 0.799, p < 0.001). VFR2 was significantly slower than VFR1 (paired t-test, p = 0.047). The degree of agreement between VFR1 and VFR2 is illustrated in figure 3.7, which shows that the bias was -2.91 cmH\textsubscript{2}O/min and the repeatability coefficient was 22.62 cmH\textsubscript{2}O/min.

The results of type II and I fatigue rates and their repeatability are shown in table 3.4.
**Figure 3.7** Bland Altman plot of mean of repeated pelvic floor fatigue rates against difference between repeated pelvic floor fatigue rates, allowing visualisation of agreement between repeated measures.

<table>
<thead>
<tr>
<th>Type II fatigue rate</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mean</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Standard deviation</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Bias</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Repeatability co-efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(all) (cmH₂O/min)</td>
<td>-219.02</td>
<td>198.81</td>
<td>14.17</td>
<td>341.75</td>
</tr>
<tr>
<td>(continent) (cmH₂O/min)</td>
<td>-250.00</td>
<td>194.82</td>
<td>43.48</td>
<td>372.62</td>
</tr>
<tr>
<td>(incontinent) (cmH₂O/min)</td>
<td>-165.50</td>
<td>198.58</td>
<td>-48.13</td>
<td>227.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type II duration (all) (minutes)</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mean</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Standard deviation</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Bias</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Repeatability co-efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(all)</td>
<td>2.6</td>
<td>1.7</td>
<td>0.48</td>
<td>3.88</td>
</tr>
<tr>
<td>(continent)</td>
<td>2.1</td>
<td>1.2</td>
<td>0.55</td>
<td>3.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type II duration (incontinent) (minutes)</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mean</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Standard deviation</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Bias</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Repeatability co-efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(all)</td>
<td>2.5</td>
<td>1.9</td>
<td>0.34</td>
<td>3.77</td>
</tr>
<tr>
<td>(incontinent)</td>
<td>2.1</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type I fatigue rate (all) (cmH₂O/min)</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mean</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Standard deviation</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Bias</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Repeatability co-efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(continent) (cmH₂O/min)</td>
<td>-7.39</td>
<td>19.88</td>
<td>-3.19</td>
<td>37.54</td>
</tr>
<tr>
<td>(incontinent) (cmH₂O/min)</td>
<td>-9.59</td>
<td>23.17</td>
<td>-2.85</td>
<td>42.89</td>
</tr>
<tr>
<td>(incontinent) (cmH₂O/min)</td>
<td>-3.61</td>
<td>11.84</td>
<td>-3.93</td>
<td>23.52</td>
</tr>
</tbody>
</table>

**Table 3.4** The mean, standard deviation for 1<sup>st</sup> and 2<sup>nd</sup> measurements of type II fatigue rate, type II duration and type I fatigue rate, plus the bias and repeatability co-efficients for repeated measures.
Area under the fatigue curve repeatability

The area under the 1st fatigue curve (AuC1) was calculated in 67 subjects, its mean was 2397 (± standard deviation 2111) and is measured in random units. The mean area under the 2nd fatigue curve (AuC2) from 61 subjects was 2272 (± 2084). The two measurements of AuC correlated strongly and significantly (Pearson, r = 0.928, p < 0.001) and were not significantly different (paired t-test, p = 0.061). By the means of Bland Altman method, the bias of repeated AuC measures was 193 and repeatability co-efficient was 1583. The means, standard deviation and degree of agreement for AuC of continent and incontinent groups were calculated separately and are shown in table 3.5.

<table>
<thead>
<tr>
<th></th>
<th>Continent (n = 38)</th>
<th>Incontinent (n = 23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AuC1</td>
<td>3196 ± 2260</td>
<td>1284 ± 1125</td>
</tr>
<tr>
<td>AuC2</td>
<td>2917 ± 2170</td>
<td>1206 ± 1422</td>
</tr>
<tr>
<td>Bias</td>
<td>288</td>
<td>36</td>
</tr>
<tr>
<td>Repeatability co-efficient</td>
<td>1505</td>
<td>1691</td>
</tr>
</tbody>
</table>

Table 3.5 Mean standard deviation of 1st and 2nd areas under pelvic floor fatigue curves (AuC1 and Auc2 respectively), plus bias and repeatability co-efficient of repeated area measures. Random units.

Discussion

The measurement of pelvic floor squeeze pressure was found to have a low bias, suggesting good test-retest repeatability. However, the repeatability co-efficient (10.34 cmH²O) was not much lower than median VMSP1 (15 cmH²O) or VMSP2 (14 cmH²O). It could be argued that such a high degree of intra-individual variability reduces the usefulness of measuring pelvic floor squeeze pressure. However, anal canal tone, both resting and squeeze, has high intra-individual variability and this is still considered useful in both research and clinical practice. The differences in pelvic floor strength in continent and incontinent subjects and as a result of childbirth will be explored in Chapter 5, where the usefulness of measurement of pelvic floor strength will be discussed.
Pelvic floor fatigue rate was also highly variable: the bias was low (-2.91 cmH₂O/min), indicating good test-retest repeatability as in strength measurement. However, the repeatability co-efficient was greater than the mean of either first or second fatigue measurement: repeatability co-efficient of 22.61 cmH₂O/min compared with mean fatigue rates of -12.04 cmH₂O/min and -9.81 cmH₂O/min. This suggests an even greater intra-individual variability than pelvic floor strength, which is not unexpected. If a voluntary contraction is variable, presumably because of varying volition, then a sustained voluntary contraction will be more variable because the degree of volition required is greater for a longer contraction than a short one. Again, the impact on clinically important scenarios will be explored in Chapter 5. Similarly, the repeatability of the areas under the fatigue curve is highly variable, because of the involvement of the same factors of volition and following instructions.

In conclusion, then, repeatability studies of pelvic floor strength and fatigue show that although the measurement of these has good test-retest repeatability, the intra-individual variability is high. To further establish the repeatability of these measurements, inter-observer repeatability studies should be completed.

**Ultrasound pelvimetry**

Other sections of this thesis introduce the idea that cephalopelvic disproportion may be important in the childbirth-induced trauma of the pelvic floor and potential subsequent development of faecal incontinence. Before a new measure of cephalopelvic disproportion can be promoted as useful for antenatal screening, it needs to be proven repeatable and accurate. Ultrasound pelvimetry was therefore measured twice in some subjects and compared with MR scanning to determine if it is repeatable and accurate.

**Method**

Primigravid women recruited to the study of changes in EAS strength and fatigue and pelvic floor strength and fatigue during pregnancy and after delivery were also invited to undergo measurement of the anteroposterior diameter of
the pelvis by means of transabdominal ultrasound scanning – ultrasound (US) pelvimetry. A full description of the technique is given in chapter 2 and was developed from the technique described by Katanozaka et al. Ten women were measured during their pregnancy (between 11 and 38 weeks gestation) and a further five were measured in the post partum period (between six and nine months post partum). Ten primigravid women had the US pelvimetry measured twice to allow reproducibility analysis. A further five non-pregnant women who had undergone a magnetic resonance imaging (MRI) scan of the pelvis for clinical reasons also underwent US pelvimetry to allow comparison of US pelvimetry with a known, accurate measure of AP pelvis size.

All US measurements were performed by one senior ultrasonographer. The principle investigator analysed the MR pelvis images to compare US and MR measurements, independently of the senior ultrasonographer. The distance that appeared to correspond most closely with that measured by US was from the symphysis pubis to the S3 promontory. This distance was therefore measured on MR for the other four control subjects and used to compare US and MR pelvimetry.

Statistical analysis was performed using SPSS version 15 (Chicago, Illinois, USA) to compare the two US pelvimetry measurements and to compare US and MR pelvimetry. Pearson correlations were used to show the degree of correlation between two measurements and Bland Altman charts were plotted to determine the limits of agreement.

Results
The mean (± standard deviation) for the first US pelvimetry measurement was 14.75 (± 1.68) cm. Where the US pelvimetry was measured twice, the mean (± SD) of the second measurement was 14.24 (± 1.55) cm. There is a strong correlation between the two US measurements: $r = 0.925$, $p < 0.001$, Pearson correlation. The Bland Altman plot of repeated US measurements is shown in figure 3.8. The repeatability co-efficient (twice the standard deviation of the difference between repeated measures) is 1.25 cm.
US pelvimetry does not correlate with the MR measurement ($r = 0.319$, $p = 0.601$ for first US measurement, and $r = 0.23$, $p = 0.438$ for second US measurement, Pearson correlation). When the Bland Altman method was used to compare the first and second US measurements with the MR measurement, the repeatability co-efficient for the first US measurement was 4.26 cm and 3.47 cm for the second US measurement.

**Discussion**

This technique of US pelvimetry was adapted from the published results of Katanosaka *et al.* who measured the obstetric conjugate at 28 and 36 weeks of pregnancy. These two repeated measures correlated strongly ($r = 0.999$). Our
repeated measures also correlated strongly \((r = 0.925)\). However, Bland and Altman state that using correlation to compare repeated measures or compare two methods of measurement is inappropriate and give the graphical method for showing the extent of agreement.\(^{101}\) By this method, the repeatability coefficient is 1.25 cm, which is clinically insignificant. It can therefore be stated that US pelvimetry is repeatable.

The repeatability co-efficient for comparing MR with the first US measurement was 4.26 cm and with the second US measurement was 3.47 cm. This tells us that 95% of US measurements of pelvis AP diameter will fall within 4.26 cm of the true distance, as measured by means of MR scanning. Whether this is clinically significant will be assessed in chapter 6.

The control subjects were all pre-operative patients, were therefore fasted for theatre and with empty bladders. A full bladder makes the measurement of US pelvimetry easier and potentially more accurate. Increased agreement between US and MR may have been found if participants had had full bladders for the US scan.

**Summary**

In summary, the findings of this chapter on the reproducibility of measurement techniques used in this thesis are as follows:

- Anal fatigue rate is highly variable, but is repeatable.
- Area under the curve of anal fatigue rate is also highly variable.
- Pelvic floor strength is highly variable, but repeatable, as are pelvic floor fatigue rate and area under the pelvic floor fatigue curve.
- US pelvimetry is repeatable, but does not correlate with MR measurement of pelvis size in this sample.
4. External anal sphincter strength and fatigue during pregnancy and after delivery in primigravid women
Faecal incontinence is more common in females than males\textsuperscript{110} and more common in parous than nulliparous women.\textsuperscript{35} The risk of FI increases with increasing parity.\textsuperscript{39,40} There is evidence of injury to the anal sphincter morphology\textsuperscript{21,111} and function\textsuperscript{21,22,43,44,111} after vaginal delivery and more significant injury where the delivery is more traumatic (e.g. instrumental delivery).\textsuperscript{22,45} Similarly, there is evidence of changes in the innervation of the anal sphincters and pelvic floor post partum,\textsuperscript{15,21,44} again with evidence of increasingly deranged innervation with more traumatic deliveries (e.g. longer 2\textsuperscript{nd} stage of labour, delivery of higher birth weight infants, instrumental delivery)\textsuperscript{15,21} and increasing number of deliveries.\textsuperscript{21,39,43} Although FI does occur immediately post partum in some women, it is more common in the older population.\textsuperscript{110} This raises the possibility of childbirth causing an injury which does not become symptomatic until later in life. It would be very attractive to find a test which could be used post partum to identify which women are at risk of future FI.

Measurement of changes in skeletal muscle fatigue gives an indication of changes not only in the muscle itself but also its innervation. Muscle fibres can be divided into slow-twitch, fatigue-resistant type I fibres and fast-twitch, fatigue-sensitive type II fibres. A number of muscle fibres are innervated by one nerve fibre. The muscle fibres and their innervating nerve are termed a motor unit. All the muscle fibres within one motor unit consist of one fibre type. Where a muscle fibre loses its innervation and is then reinnervated, the fibre changes its type to reflect the ingrowing axon.\textsuperscript{72} Sustained gross muscle contraction will reflect not only whole muscle strength but also the proportion of type I and II muscle fibres, by examining the fatigue curve. Measuring fatigue repeatedly over time should reflect changes in the muscle and its innervation by examining changes in the fatigue rate and curve.

This study aims to establish how anal manometry and fatigue alter during pregnancy and after delivery in primigravid women. Since childbirth causes damage to the muscles and innervation of the pelvic floor, and since fatigue reflects function of both the muscles and their innervation, changes in fatigue might identify those women sustaining an initial insult which will result in FI. If so, this could potentially be a screening tool to identify women at risk of future
If such a test were identified, it would only gain general acceptance by new mothers and their health professionals, if it were simple to carry out and analyse, relatively non-invasive and acceptable to women.

Method

Primigravid women booking for antenatal care at Withington Community Hospital or Wythenshawe Hospital were invited to participate in this prospective, observational study of changes in anal manometry, anal fatigue, pelvic floor strength and pelvic floor fatigue during pregnancy and after delivery. Full details of the methodology are given in Chapter 2: Methods. In summary, participants underwent measurement of anal sphincter manometry and fatigue and pelvic floor strength and fatigue at booking, during the third trimester and at least four months post partum. Pelvic floor symptoms were quantified at these time points using the Vaizey score of FI, Manchester Health Questionnaire (MHQ) to assess FI-related quality of live, and Kings Health Questionnaire (KHQ) to assess the impact of urinary symptoms. Some women were approached later in their pregnancy, at the 20 week gestation anomaly scan, and only underwent one measurement of anal and pelvic floor strength and fatigue during pregnancy. Women were also invited to undergo measurement of the obstetric conjugate by means of ultrasound scanning. Full methodology and results are reported in Chapter 6: Cephalopelvic disproportion.

Anal manometry was measured using a water-filled micro-balloon and a station pull-through technique. Fatigue was measured during a 22 second sustained voluntary contraction immediately after manometry measurement. Subjects were given a 2 minute rest period before repeating the fatigue measurement.

Pelvic floor strength was measured using a blue-tooth enabled Peritron (Cardio Design, Australia), an air-filled vaginal probe. Full methodology is given in Chapter 2: Methods and results are given in Chapter 5: Pelvic floor strength and fatigue.
Results of anal manometry, anal fatigue, pelvic floor strength and fatigue, delivery information and ultrasound pelvimetry data were collated in Excel (Microsoft, Redmond, Washington, USA) and statistical analysis was carried out in SPSS version 15 (Chicago, Illinois, USA). Parametric data were compared between time points with paired t-test and between groups with a t-test. Non-parametric data were compared between time points with a Wilcoxon signed ranks test and between groups with a Mann-Whitney U test. Where repeated measurements were compared between different time points, an analysis of variance was carried out.

Pilot study

A pilot study of changes in anal pressures and fatigue was carried out in 2000 and 2001 with an air-filled probe measuring gross anal canal pressures. These data were collected by a colleague and passed to myself for analysis. Twenty-seven women were included in the study, but anorectal manometry was incomplete in four and a further four delivered by Caesarean section, two electively and two emergency.

Nineteen primigravid women, mean age 30.4 years (range 21 to 40), underwent measurement of anal resting pressure, maximum anal squeeze pressure and anal fatigue rate over a 20 second voluntary contraction at a median of 33 weeks gestation (range 28 to 38 weeks) and a median of 11 weeks post partum (range 9 to 19 weeks).

Table 4.1 summarises the manometry and fatigue measurements. There was no significant difference in MRP post partum. However, MSP was significantly lower post partum and the fatigue rate was significantly slower (i.e. less negative) post partum, indicating a greater resistance to fatigue. There was no significant difference in the fatigue rate index (FRI) post partum.
<table>
<thead>
<tr>
<th></th>
<th>Pre delivery</th>
<th>Post partum</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting pressure (cmH$_2$O)</td>
<td>57.08 ± 13.61</td>
<td>51.09 ± 11.91</td>
<td>0.1 (paired t-test)</td>
</tr>
<tr>
<td>Squeeze pressure (cmH$_2$O)</td>
<td>106.50 ± 43.64</td>
<td>75.54 ± 45.56</td>
<td>&lt; 0.001 (paired t-test)</td>
</tr>
<tr>
<td>Fatigue rate (cmH$_2$O/min)</td>
<td>-129.45 ± 74.68</td>
<td>-76.07 ± 54.83</td>
<td>0.001 (paired t-test)</td>
</tr>
<tr>
<td>FRI (minutes)</td>
<td>1.23 ± 1.49</td>
<td>1.41 ± 1.27</td>
<td>0.09 (Wilcoxon signed rank sum)</td>
</tr>
</tbody>
</table>

Table 4.1 The mean ± standard deviation of stated measurements/calculations pre and post delivery in the pilot study. Table reproduced from Cattle et al.$^{112}$

Typical anal fatigue measurements pre and post delivery in one subject are illustrated in Figure 4.1.

![Anal canal fatigue](image)

Figure 4.1 Example of graph of anal canal pressure during a maximal voluntary contraction, sustained over 20 seconds, pre and post delivery. The linear best fit lines are applied and adjacent equation indicates the slope and intersection of the line. Figure reproduced from Cattle et al.$^{112}$

No effects of perineal trauma, episiotomy or instrumental delivery could be found on squeeze pressure, fatigue rate, FRI or quality of life measure (see table 4.2). Nor was any correlation between degree of perineal tear or length of 2nd stage of labour and squeeze pressure or fatigue rate found.
| Table 4.2 | Mean and standard deviation (SD) of the maximum squeeze pressure (MSP) and fatigue rate (FR) in women who did or did not sustain a perineal tear, undergo episiotomy or instrumental delivery. There were no statistically significant differences between the means shown. Table reproduced from Cattle et al.\textsuperscript{112} |
| --- | --- | --- | --- |
| | MSP (mean ± SD) | FR (mean ± SD) |
| Perineal tear? | | |
| Yes (n=10) | 74.71 ± 48.28 | -70.25 ± 63.80 |
| No (n=10) | 74.24 ± 43.24 | -84.59 ± 43.65 |
| Episiotomy? | | |
| Yes (n=6) | 58.94 ± 24.04 | -61.49 ± 30.52 |
| No (n=14) | 81.13 ± 50.27 | -84.25 ± 60.75 |
| Instrumental delivery? | | |
| Yes (n=7) | 63.35 ± 40.62 | -87.86 ± 63.71 |
| No (n=13) | 80.47 ± 47.06 | -71.80 ± 49.40 |

Sixteen women reported new symptoms of anal incontinence post partum; two of these to solid stool (one occasional, one sometimes), one to liquid stool (occasional), and 13 to flatus (eight occasional, three sometimes, two frequent). There were no statistically significant differences in post partum resting pressure (48.05 ± 8.44 cmH\textsubscript{2}O in continent mothers, vs 53.06 ± 12.61 cmH\textsubscript{2}O in incontinent mothers), squeeze pressure (82.51 ± 51.46 cmH\textsubscript{2}O in continent mothers, vs 75.64 ± 43.08 cmH\textsubscript{2}O in incontinent mothers), fatigue rate (-90.85 ± 56.39 cmH\textsubscript{2}O/minute in continent mothers, vs -73.04 ± 54.10 cmH\textsubscript{2}O/minute in incontinent mothers) or FRI (1.02 ± 0.45 minutes in continent mothers, vs 1.60 ± 1.51 minutes in incontinent mothers) between women who did and did not report anal incontinence post partum.\textsuperscript{112}

**Current study**

With these results in mind, a larger prospective, observational study was planned, which aimed to use a more precise technique to document changes in anal manometry, EAS fatigue, pelvic floor strength, pelvic floor fatigue and anal and urinary symptoms during pregnancy and after delivery, with the hypothesis that one of these may provide a simple screening test to determine the likelihood of developing future pelvic floor symptoms. Details of the labour, delivery and size of the baby were also recorded in order to identify potential risk factors predisposing to increased trauma.
Recruitment data
One hundred and seventy five women were approached to participate in the study, 30 agreed, giving a recruitment rate of 17%. Of those who gave reasons for not wishing to participate, 19 expressed distaste at the idea of any anorectal instrumentation and a further 8 felt that the study was invasive, 10 were not interested in participating, 14 had other health problems making them unwilling to participate, 8 were too busy and 3 thought they might have participated if it hadn’t been their first pregnancy.

Participants
Thirty primiparous women (mean age 30.1, standard deviation 4.42 years) were included in the study. Twenty were measured at booking (between gestations of 9 and 18 weeks), twenty one were measured later in their pregnancy (between 20 and 41 weeks gestation). Twelve were measured twice during the pregnancy. Two withdrew from the study during their pregnancy, one who miscarried, the other moved away. Twenty women were measured post partum. Three withdrew because they no longer wished to continue in the study, another one moved away and a further three did not reply to requests to complete the study despite multiple attempts to contact them.

Anal manometry and fatigues at booking
In the 21 women measured at booking, median anal maximum resting pressure (MRP) was 68.9 cmH₂O (range 18 – 139 cmH₂O) at booking and median anal maximum squeeze pressure (MSP) was 79.0 cmH₂O (range 24 – 235 cmH₂O). Fatigue rate was measured twice, the first measurement was termed FR1 and the second FR2. Median FR1 was -82.26 cmH₂O/min (range -386.88 – 87.84 cmH₂O/min) and median FR2 was -60.57 cmH₂O/min (range -185.58 – 40.42 cmH₂O/min). Fatigue rate index (FRI) was calculated for each measurement of fatigue. Median FRI1 was 0.672 minutes (range -1.613 – 2.991 minutes) and median FRI2 was 0.979 minutes (range -0.996 – 7.046 minutes). Fatigue rates for the first steep part of the fatigue curve (type II fatigue rate) and second shallower part of the fatigue curve (type I fatigue rate) were also measured and
Anal manometry and fatigues in later pregnancy

In the 20 women measured at or after 20 weeks gestation, median MRP was 69.5 cmH\(_2\)O (range 31 – 150 cmH\(_2\)O) and median MSP was 108 cmH\(_2\)O (range 20 – 240 cmH\(_2\)O). Median FR1 was -110.7 cmH\(_2\)O/min (range -216.18 – 93.24 cmH\(_2\)O/min) and median FR2 was -90.9 cmH\(_2\)O/min (range -282.6 – 98.46 cmH\(_2\)O/min). Median FRI1 was 0.744 minutes (range -4.564 – 1.707 minutes) and FRI2 was 0.840 minutes (range -0.650 – 10.329 minutes). Types II and I fatigue rates for anal fatigues later in pregnancy are also shown in Table 4.3.

Comparison of anal manometry and fatigues between beginning and end of pregnancy

Twelve women underwent measurement of anal manometry and fatigue rate at booking (median 13 weeks gestation, range 9 – 17 weeks) and later in the pregnancy (median 38 weeks gestation, range 35 – 41 weeks). There was no difference in MRP, MSP, FR1, FR2, FRI1, FRI2 or type II or type I fatigue rates between the two stages of pregnancy (Wilcoxon signed ranks test, p ≥ 0.05). Univariate analysis, comparing both readings of FR at each time point, also showed no difference in anal fatigue rate during pregnancy (p = 0.459).

Anal manometry and fatigues post partum

Twenty women underwent measurement of anal manometry and fatigue rate between four and ten months post partum (median, six months). Median MRP was 81.5 cmH\(_2\)O (range 46 – 114 cmH\(_2\)O) and median MSP was 99.5 cmH\(_2\)O (range 24 – 324 cmH\(_2\)O). Median FR1 was -117.18 cmH\(_2\)O/min (range -297.36 – -13.32 cmH\(_2\)O/min), median FR2 was -116.82 cmH\(_2\)O/min (range -307.87 – 12.96 cmH\(_2\)O/min), median FRI1 was 0.847 minutes (range 0.187 – 1.577 minutes), and median FRI2 was 0.902 minutes (range -2.701 – 14.306 minutes). Types II and I FR are also shown in Table 4.3.
Comparison of anal manometry and fatigues before and after delivery

In order to compare anal manometry before and after delivery, one measurement from during the pregnancy was compared with post partum measurements. Where two measurements were available, the earlier ones were used. Wilcoxon signed ranks tests were used.

Maximum resting pressure was significantly higher post partum than pregnancy values ($p = 0.004$). There was no significant difference in MSP ($p = 0.24$), FR1 ($p = 0.601$) or FR2 ($p = 0.184$). However, where both fatigue measurements for each time point (during pregnancy or post partum) are compared in one ANOVA, there appears to be a difference between during pregnancy anal fatigue rate and post partum anal fatigue rate which approaches statistical significance ($p = 0.053$).

Delivery details and impact on anal manometry and fatigues

Of the participants who were measured post partum, 11 had a spontaneous vaginal delivery, five had ventouse delivery, two had forceps delivery, one had an elective Caesarean section and one had an emergency Caesarean section. All subjects were successfully delivered of a single live infant between 35 and 42 weeks gestation. Mean birth weight was $3.53 \pm 0.59$ kg and mean head circumference was $35.34 \pm 1.56$ cm.

Twelve had spontaneous onset of labour and eight underwent artificial induction of labour. Four subjects received induction of labour with Prostin gel, five underwent artificial rupture of membranes, three after spontaneous onset of labour and two to induce labour, and four received Syntocinon infusion, two after spontaneous onset of labour and two to induce labour. The mean length of the first stage of labour was 6 hours, 40 minutes (range 1 hour 15 minutes to 14 hours). The mean length of the second stage of labour was 98 minutes (range 13 minutes to 205 minutes). Two subjects who delivered vaginally had
an intact perineum, nine underwent episiotomy, four had a 1\textsuperscript{st} degree tear, 2 had a 2\textsuperscript{nd} degree tear and 1 had a 3\textsuperscript{rd} degree tear.

Eight subjects had a longer than average 2\textsuperscript{nd} stage of labour. There was no effect on anal manometry or fatigue rate (MRP, MSP, FR1 or FR2) between those who had a longer or shorter 2\textsuperscript{nd} stage of labour (Wilcoxon signed ranks test). Nor was there any difference in anal manometry or fatigue rate between those who underwent instrumental delivery (7 subjects) or had an intact perineum (4 subjects, including the 2 who delivered by Caesarean). There was no effect of a long 2\textsuperscript{nd} stage of labour, instrumental delivery, perineal trauma or episiotomy on an analysis of variance including both post partum fatigue rate measurements.

There was no significant difference in post partum MRP, MSP, FR1 or FR2 between women delivered of infants with greater birth weight or larger head circumference. The effect of birth weight and head circumference on post partum fatigue measurements was analysed using an ANOVA, but again no significant difference was found.

**Pelvic floor symptoms and impact on quality of life during pregnancy and after delivery**

The median Vaizey score of faecal incontinence at booking was 0 (range 0 – 4), the median Manchester Health Questionnaire (MHQ) measure of impact of faecal incontinence on quality of life was 0 (range 0 – 75) and the median Kings Health Questionnaire (KHQ) measure of impact of urinary incontinence on quality of life was 18.67 (range 0 – 98.67). Later in pregnancy the median Vaizey was 0 (range 0 – 6), median MHQ was 0 (range 0 – 72.5) and median KHQ was 25 (range 0 – 120.67). Post partum, the median Vaizey was 0 (range 0 – 12), median MHQ was 17.5 (range 0 – 130.83) and median KHQ was 25 (range 0 – 174.22). There was no statistically significant difference in the Vaizey or MHQ between early and late pregnancy or between during pregnancy or post partum (Wilcoxon signed ranks test). The KHQ was significantly higher
during later pregnancy (p = 0.013) but there was no significant difference between KHQ at booking and post partum.

There was no difference in symptom or quality of life scores between those with longer or shorter 2\textsuperscript{nd} stage of labour, between those who had intact perineum or not or those who had instrumental delivery or not.

There was no significant difference in Vaizey, MHQ or KHQ between those with a higher than average birth weight baby and those with a lower than average birth weight baby. The KHQ was significantly lower in those with a baby greater than 4 kg (Mann-Whitney U test, p = 0.025), but this is likely to be a statistical anomaly due to the small numbers (5 subjects delivered an infant weighing over 4 kg). Similarly, there was no statistically significant difference in Vaizey, MHQ or KHQ between those delivered of infants with smaller than average or larger than average head circumference.
<table>
<thead>
<tr>
<th></th>
<th>Booking (n = 21)</th>
<th>Third trimester (n = 20)</th>
<th>Post partum (n = 20)</th>
<th>p value (Wilcoxon signed ranks test)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MRP cmH\textsubscript{2}O</strong></td>
<td>68.9 (18 – 139)</td>
<td>69.5 (31 – 150)</td>
<td>81.5 (46 – 114)</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>MSP cmH\textsubscript{2}O</strong></td>
<td>79.0 (24 – 235)</td>
<td>108.0 (20 – 240)</td>
<td>99.5 (24 – 324)</td>
<td>0.240</td>
</tr>
<tr>
<td><strong>FR1 cmH\textsubscript{2}O/min</strong></td>
<td>-82.3 (-386.7 – 87.8)</td>
<td>-110.7 (-216.2 – 93.2)</td>
<td>-117.2 (-297.4 – -13.3)</td>
<td>0.601</td>
</tr>
<tr>
<td><strong>FRI1 minutes</strong></td>
<td>0.672 (-1.613 – 2.991)</td>
<td>0.744 (-4.564 – 1.707)</td>
<td>0.847 (0.187 – 1.577)</td>
<td></td>
</tr>
<tr>
<td><strong>TIIFR1 cmH\textsubscript{2}O/min</strong></td>
<td>-1161.9 (-3915.7 – -334.2)</td>
<td>-1092.1 (-4367.7 – -148.0)</td>
<td>-1314.6 (-4136.2 – -219.6)</td>
<td></td>
</tr>
<tr>
<td><strong>TIFR1 cmH\textsubscript{2}O/min</strong></td>
<td>-47.0 (-280.9 – 94.0)</td>
<td>-49.9 (-161.6 – 115.2)</td>
<td>-56.2 (-280.6 – -12.1)</td>
<td></td>
</tr>
<tr>
<td><strong>FR2 cmH\textsubscript{2}O/min</strong></td>
<td>-60.6 (-185.6 – 40.4)</td>
<td>-90.9 (-282.6 – 98.5)</td>
<td>-116.8 (-308.0 – 13.0)</td>
<td>0.184</td>
</tr>
<tr>
<td><strong>FRI2 minutes</strong></td>
<td>0.979 (-0.996 – 7.046)</td>
<td>0.840 (-0.650 – 10.329)</td>
<td>0.902 (-2.701 – 14.306)</td>
<td></td>
</tr>
<tr>
<td><strong>TIIFR2 cmH\textsubscript{2}O/min</strong></td>
<td>-1000.1 (-5771.4 – -89.4)</td>
<td>-1286.5 (-4482.4 – -252.0)</td>
<td>-1467.2 (-4318.9 – -210.4)</td>
<td></td>
</tr>
<tr>
<td><strong>TIFR2 cmH\textsubscript{2}O/min</strong></td>
<td>-16.2 (-148.1 – 139.2)</td>
<td>-35.1 (-129.8 – 100.8)</td>
<td>-57.4 (-156.2 – 73.6)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Anal manometry and fatigue rates in primigravid women at booking, after 21 weeks gestation (third trimester) and post partum. Median and range are given for each value. Annotation: MRP, maximum resting pressure; MSP, maximum squeeze pressure; FR1, 1\textsuperscript{st} measurement of fatigue rate; FRI1 fatigue rate index of 1\textsuperscript{st} fatigue measurement; TIIFR1, type II fatigue rate of 1\textsuperscript{st} fatigue measurement; TIFR1, type I fatigue rate of 1\textsuperscript{st} fatigue measurement; FR2, 2\textsuperscript{nd} measurement of fatigue rate; FRI2, fatigue rate index of 2\textsuperscript{nd} fatigue measurement; TIIFR2, type II fatigue rate of 2\textsuperscript{nd} fatigue measurement; TIFR2, type I fatigue rate of 2\textsuperscript{nd} fatigue measurement.
Discussion

Findings
The pilot data showed a preservation of anal canal resting pressure post partum and a fall in pressure on voluntary contraction. These findings are in keeping with the published literature.\textsuperscript{43,44} The pilot study also found a fall in fatigue rate post partum. This was a novel finding and is perhaps unsurprising, given the previous finding of reduced fatigue rate index in incontinent subjects\textsuperscript{80,81} and the association between childbirth and development of FI. However, although Marcello \textit{et al}\textsuperscript{80} report a slower fatigue rate in their results table, they do not report any statistical comparison between the FR (rather than the FRI) of continent and incontinent subjects and in their discussion they state “most patients with incontinence usually have a rapid rate of fatigue”.\textsuperscript{80} Telford \textit{et al}\textsuperscript{81} found no statistical difference between the FR of continent and incontinent subjects. Only when the FR was combined with the MSP, which was also not statistically different between continent and incontinent subjects, to calculate the FRI did this become statistically different between continent and incontinent subjects. Previous work in our group showed a significant difference between the FR of continent and incontinent women, but no difference in the FRI\textsuperscript{102}.

In the current study, anal manometry and fatigue were measured early and late in pregnancy. No significant difference was found between early and late pregnancy in any measurement. This is in keeping with other studies, reporting no effect of pregnancy on anal sphincter morphology or function\textsuperscript{111} and preservation of antenatal sphincter function in those delivered by elective Caesarean section.\textsuperscript{15,22,84} This then allowed comparison of any antenatal manometry measurement with post partum measurements.

The current study found a significant rise in MRP post partum, no significant change in MSP and faster fatigue rate post partum, which did not reach statistical significance. These findings are in direct contradiction to the pilot study findings and the published literature. Anal canal resting pressure was found to fall post partum in some studies\textsuperscript{22,32,43} and remain unchanged in
others. Some have documented recovery of MRP in the months post partum, but not to levels greater than antenatally.

A reduced MSP, as found in the pilot study is in keeping with the published literature – a fall in anal canal voluntary contraction after vaginal delivery is well documented. Elective Caesarean section appears to be protective. The pilot findings were not confirmed in the current study. Post partum measurements were made a median of 11 weeks after delivery in the pilot study. Since some recovery in MSP has been reported in the literature, post partum measurements in the current study were made 6 months post partum in order to allow for this initial recovery to have occurred. This may explain the differing results.

A slower fatigue rate of the anal canal post partum was found in the pilot study. This helps to uphold the hypothesis of childbirth causing the initial insult to the pelvic floor, and post partum manometry findings in keeping with those found in incontinent subjects, who have a slower fatigue rate. The current study found a faster fatigue rate in post partum subjects, although this difference did not reach statistical significance, which contradicts both previous findings and the hypothesis based on the published literature.

No statistically significant effect of any factor about the labour, route of delivery, or infant factors were found to have any effect on the measured anal canal function in either the pilot or current study. Study subjects were divided into those who had had a longer than average length 2nd stage of labour or not, as per the method used by Allen et al, who showed a difference in the EMG of the pelvic floor in women who had a longer than average 2nd stage of labour. This method was also used to compare women who delivered babies of greater than average birth weight or not, or greater than average head circumference or not. Although there are multiple published studies showing the detrimental effect on the pelvic floor of forceps delivery, prolonged 2nd stage of labour or the delivery of large babies, it may be that the number of participants was too small in this study. Similarly, no difference in effect on symptoms of different delivery route was found, again perhaps because of the small study size. Other studies
showing the effect of mode of delivery on the development of symptoms have included 240 to nearly 1000 women.\textsuperscript{35-38}

**Conflicting results**

Why then do the two studies contradict each other? Different manometry equipment was used in the pilot study from the current study. The Myomed 932 (Enraf Nonius, Netherlands) system was used in the pilot study, which consists of an 8 mm air-filled probe, connected by air-filled plastic tubing to the portable unit. It measures gross anal canal pressures. In the current study a water-filled micro-balloon, connected via water-filled non-distensible tubing to the transducer and laptop, was used to measure resting and squeeze tone at 1 cm intervals along the anal canal. A water-filled non-distensible system can be argued to give more accurate results, because of the non-compressible nature of water. Simpson\textsuperscript{59} compared five manometry systems and reported that the Peritron – an air-filled probe measuring gross anal canal pressures, similar to the Myomed – consistently measured lower resting and squeeze pressures. This may be because bench testing of the Peritron reported that it required higher pressures to deform the probe, thereby dissipating some of the pressure produced by the anal canal in deforming the probe before the pressure changes are transmitted to the transducer.\textsuperscript{59} It may be, therefore, that the pilot study recorded lower pressures than the current study. However, this would not explain the different findings, because each subject was only measured with one device throughout her participation in the study. Therefore the findings are the result of differences in a subject, not differences between measurement techniques.

A gradual drift in the accuracy of the water-filled system during the study period could explain these conflicting results. A gradual increase in sensitivity, where steadily increasing pressures, higher than the true value, were recorded over time, would give an apparent rise in an unchanged pressure, fail to show a true fall in pressure, and a steeper fatigue rate where higher pressures are magnified more than lower pressures. However, the portable manometry equipment was calibrated regularly against equipment producing known
pressures and no drift in either the gain (the sensitivity of the equipment) or the offset (the set zero) were detected in the last 19 months of the study.

Different investigators carried out the pilot and current studies. It might be possible that differing techniques in recording anal manometry and fatigue between the two investigators explain the conflicting findings. However, one investigator carried out all measurements in one subject and findings report changes within subjects, rather than between subject groups, making it unlikely that differing measurement techniques would explain conflicting findings. Also, the investigator in the current study was taught the manometry and fatigue technique by both a previous researcher within the group and by an expert in anorectal physiology studies and urodynamics working in the region. One investigator examined the raw data from both studies, making flawed statistical analysis unlikely to contribute to findings in one study and not the other.

As previously discussed, the pilot study measured women a median of 11 (range 9 to 19) weeks post partum. Since there is a potential for recovery of the pelvic floor over at least the first 2-3 months post partum, the current study was designed to take post partum measurements at a time point when recovery was likely to have occurred but before participants may have moved away, returned to employment or become lost to follow up in other ways. The findings of unchanged MSP and FR could be explained by this difference in study design, indicating a full recovery of voluntary contraction, brief and sustained, 4 months post partum. The rise in MRP cannot be explained this way.

If the differences in results cannot be explained by differences between the techniques, can we accept both sets of results? It is possible that neither study was large enough to reflect the true effects of childbirth on anal manometry and fatigability and that statistically significant findings are a type I error, where a significant result is obtained where no such true effect exists, and also a type II error, where no significant effects are obtained where in actual fact changes do occur which are not reflected in the statistics. Given the high degree of
variability in both MSP\textsuperscript{55} and fatigue rate (see Chapter 3: Reproducibility), this is most likely to be the case.

**The next step**
To determine which results reflect the true picture, a larger study is required. The aim was to carry out a larger study than the pilot study. The eventual size of the current study was essentially no larger than the pilot study. Various reasons for this exist. Although midwife involvement was encouraged and the study was designed with involvement of the community midwives, the midwives did not engage with active recruitment of participants. Therefore a few weeks were lost before it was realised that all potential participants had to be approached by the investigator in person. It was also thought initially that enough numbers could be recruited through approaching women booking with two particular community midwife teams. When it was realised that the recruitment rate was poor, primigravid women booking at Wythenshawe were also approached, as were women further on in their pregnancy than booking. This also resulted in missing potential participants from Wythenshawe earlier in the study period.

Data were missing from late pregnancy in a number of women who delivered before the investigator contacted them to complete the late pregnancy measurements. The only difference measured between early and late pregnancy was a temporary deterioration in urinary-related quality of life which is a known feature of being heavily pregnant. Other investigators have found no difference in pelvic floor parameters as a result of pregnancy itself rather than childbirth. A future, simplified study could therefore eliminate the late pregnancy measurements.

Various challenges exist in repeating the study to include larger numbers. The majority of those who gave a reason for not wishing to participate expressed distaste at the idea of anorectal instrumentation or felt that the study was invasive. This is a cultural issue, with particularly British people finding
discussion of the anorectum difficult. The European women approached were much more willing to participate.

**Does the study answer our aims?**

The study aimed to establish how anal manometry and fatigue alter during pregnancy and after delivery in primigravid women. It also aimed to determine whether FR could be used as a screening tool to identify those women at risk of developing FI in the future. The pilot study did appear to answer the first aim, showing no change in MRP, a fall in MSP and a reduction in FR following vaginal delivery in primigravid women. However, the current study has not confirmed these findings.

A secondary aim, based on the results of first, was to determine if any measurement of pelvic floor function, specifically fatigue rate, could be introduced as a screening test, identifying women at risk of future FI as a result of childbirth. Such a test is required because the majority of women develop the symptoms in later life,\(^1\) rather than immediately post partum, and many do not discuss this embarrassing condition with their health care professionals. However, to gain widespread acceptance among new mothers, any potential screening test must be acceptable. Anorectal instrumentation does not appear to be acceptable to many British women approached to take part in the study. Vaginal instrumentation may be more acceptable, given the widespread uptake of cervical screening. Comparison of the acceptability of anal manometry and pelvic floor strength measurement were not included in this study. To gain acceptance among health professionals, the test should also be simple and safe to carry out, with inexpensive equipment, which fatigue measurement does fulfil. A new screening test must not only be acceptable, simple, safe and inexpensive, it must also be sensitive and specific for the disease process it aims to identify. This will be discussed further in Chapter 7: Discussion, but the high degree of variability in the measurement of voluntary contraction make it unlikely that fatigue alone will be useful as a screening test in the individual patient.
Summary

Although the pilot study showed a fall in anal squeeze pressure and reduced fatigue rate post partum, these results were not confirmed by the current study. This may be because of insufficient numbers to detect small changes in a variable parameter, or that the true fall in squeeze pressure and reduced fatigue rate measured by the pilot study had recovered by the time point at which anal manometry and fatigue were measured in the current study.
5. Pelvic floor strength and fatigue
It has been known for a long time that the pelvic floor muscles (PFM), and puborectalis in particular, are important in the maintenance of continence. However, although assessment of the PFM contraction is an integral part of the assessment of the incontinent patient, this is usually a clinical assessment by urologists, urogynaecologists and physiotherapists of women with urinary incontinence. Methods of assessment vary, including clinical examination, tests of muscle function – both strength generation and EMG activity – and visualisation of muscle function with ultrasound and magnetic resonance imaging. In patients with FI, assessment of PFM contraction is often limited to palpation of puborectalis per rectally and a comment on the anorectal angle in a defaecating proctogram. No attempt is made to quantify PFM contraction in routine clinical assessment of FI patients in the way that anal sphincter function is quantified.

This study aims to determine if measurement of PFM strength and fatigue would be useful in the routine clinical assessment of patients with FI, by first comparing pelvic floor strength and fatigue between continent and incontinent women, to determine if a statistically significant difference exists between these patient groups. It then goes on to measure PFM strength and fatigue during pregnancy and after delivery to see if childbirth alters pelvic floor strength or fatigue. If childbirth significantly alters the ability of the PFM to contract, and if PFM strength is reduced in FI patients, this may be another mechanism contributing to the injury resulting in post partum FI.

**Method**

After obtaining informed consent, participants underwent anal manometry and fatigue measurement, using a water-filled, microballoon and portable equipment, as described in Chapter 2. They then underwent measurement of pelvic floor strength and fatigue, using an air-filled probe and blue-tooth enabled Peritron (Cardio Design, Australia), as fully described in Chapter 2. In the left lateral position, the covered, lubricated probe was placed in the vagina and the pressure was zeroed. Participants were asked to perform a maximal pelvic floor squeeze and correct technique was ensured by observing a visible cranial
movement of the vaginal probe associated with a rise in vaginal pressure. Pressure recording was then commenced, using PhysioLog Pro software (PhysioLog Products, Pty Ltd, Australia), participants were asked to perform a maximal pelvic floor contraction, relax, then hold a pelvic floor contraction for 20 seconds. They repeated the maximal and prolonged contractions after a two minute rest period. Parity and route of delivery were also noted for each participant.

Incontinent women were recruited from the clinic and prior to undergoing treatment for their incontinence. Continent women booking at Wythenshawe or Withington Community Hospitals with their first pregnancy were approached to take part in the study comparing external anal sphincter strength and fatigue during pregnancy and after delivery. Full recruitment information is given in Chapter 4. Initial analysis showed a significant difference in pelvic floor strength between continent and incontinent women, but also significant age difference. Therefore, continent women aged 40 to 70 were approached to participate when they were admitted to hospital for unrelated conditions, e.g. for elective surgery or endoscopic examinations. Relatives and acquaintances also volunteered to participate. Exclusion criteria for continent controls were faecal incontinence, severe urinary incontinence (mild stress urinary incontinence was not excluded) or a history of anal surgery, e.g. haemorrhoidectomy.

Data were stored in PhysioLog data files and analysed in Excel (Microsoft, Redmond, Washington, USA) to obtain the following:

- maximal squeeze pressure (VMSP): the best pressure generated over all four contractions (cmH₂O);
- fatigue rate (VFR1 or VFR2): rate of fall in pressure over 20 seconds from beginning of sustained contraction (cmH₂O/min);
- type II fatigue rate (TIIFR1 or TIIFR2): rate of fatigue from the beginning of the sustained contraction to the lowest pressure in the first downwards trend (cmH₂O/min);
• type II duration: the duration of the first downward trend, from beginning of the sustained contraction to the lowest pressure in the first downwards trend (secs);
• type I fatigue rate (TIFR1 or TIFR2): rate of fatigue after the first downwards pressure trend (cmH$_2$O/min);
• area under the fatigue curve (AuC1 or AuC2): by adding the pressure above baseline for each data point, from the commencement of pressure rise to 20 seconds beyond the first steep rise in pressure (random units).

Both pelvic floor pressure and fatigue rate were normally distributed, therefore parametric tests were used to compare groups (t-test) or time points (paired t-test). Where repeated measures at repeated time points were compared, an analysis of variance was used.

Comparison of pelvic floor strength and fatigue in continent and incontinent women

Eighty five subjects underwent measurement of pelvic floor strength and fatigue rate. This included 39 incontinent women, 24 primigravid women taking part in the study of the effects of pregnancy and delivery on the pelvic floor, and 22 other continent women. In 68 subjects the technique was good and fatigue rates were able to be measured, 13 were unable to hold the probe in, 3 had a poor technique and insertion of the probe was painful in one. Those who were unable to hold the probe in were assumed to have a pelvic floor squeeze pressure of zero. The pelvic floor squeeze pressure and fatigue rate in the continent and incontinent subjects are shown in table 5.1.

<table>
<thead>
<tr>
<th></th>
<th>Continent</th>
<th>Incontinent</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMSP (cmH$_2$O)</td>
<td>26.95 ± 15.68</td>
<td>8.82 ± 12.74</td>
</tr>
<tr>
<td>VFR1 (cmH$_2$O/min)</td>
<td>-17.08 ± 21.24</td>
<td>-4.86 ± 10.33</td>
</tr>
<tr>
<td>VFR2 (cmH$_2$O/min)</td>
<td>-13.96 ± 17.78</td>
<td>-2.78 ± 6.45</td>
</tr>
</tbody>
</table>

Table 5.1 Pelvic floor strength (VMSP) and 1$^{st}$ and 2$^{nd}$ pelvic floor fatigue rates (VFR1 and VFR2 respectively) in continent and incontinent subjects.
Age relationship

Although there was a statistically significant difference between the pelvic floor strength and fatigue rate of the continent and incontinent groups, there was also a significant difference in the mean age of the two groups. Age correlates negatively and significantly but not strongly with pelvic floor strength (Pearson correlation, $r = -0.368$, $p = 0.001$). The age distribution of the two groups is shown in table 5.2.

<table>
<thead>
<tr>
<th>Age range</th>
<th>Continent (n = 43)</th>
<th>Incontinent (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-24</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>25-29</td>
<td>8</td>
<td>1</td>
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<tr>
<td>30-34</td>
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<td>70-74</td>
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<td>2</td>
</tr>
<tr>
<td>75-79</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5.2 Mean, standard deviation and number of subjects in each age bracket for continent and incontinent subjects.

Pelvic floor strength in continent and incontinent women

After analysis of the age distribution of participants and deliberate attempt to recruit continent women over the age of 50 years, it was decided to exclude those under the age of 35 from analysis, to remove the bias of age on the comparison between continent and incontinent subjects. After exclusion of those under the age of 35, there is no statistically significant difference between the ages of the two groups (t-test, $p = 0.094$), but there remains a significant difference between the pelvic floor strength of continent ($27.17 \pm 18.16 \text{ cmH}_2\text{O}$) and incontinent ($8.97 \pm 12.88 \text{ cmH}_2\text{O/min}$) subjects ($p < 0.001$). This analysis is based on an assumption of zero pelvic floor squeeze pressure in those unable to hold the vaginal probe in. However, there remains a significant difference in pelvic floor squeeze pressure between continent and incontinent subjects when
these subjects are excluded (p = 0.002). Table 5.3 shows the results of measurements of pelvic floor strength and fatigue and anal manometry and fatigue in subjects over the age of 35.

**Pelvic floor fatigue in continent and incontinent women**

The first and second pelvic floor fatigue rates differ significantly between continent and incontinent women – they are significantly slower in incontinent women (see table 5.3). If both measures of fatigue are compared between groups in an ANOVA, there is still a significant difference between continent and incontinent women: p = 0.01, a stronger significance than either fatigue rate alone. The area under the fatigue curve (VAuC) also differed significantly between continent and incontinent subjects. However, analysis of types II or I fatigue rate showed no difference between continent and incontinent subjects when both measurements were combined in one ANOVA, nor in the duration of type II fatigue.

**Positive fatigue rates**

Analysable fatigue rates were measured in 48 subjects. Some of these were positive, i.e. the pressure rose over time, rather than falling. In 48 subjects, 29 only gave negative fatigue rates, 15 only gave positive fatigue rates and in 4 the fatigue rate was positive on one measurement and negative on the other. In some subjects the fatigue rate was only measured once, for technical reasons. Of a total of 90 fatigue measurements, 31 were positive. Therefore 34% of fatigue rates were positive. In continent subjects, 16 produced only negative fatigue rates and 5 produced only positive fatigues or mixed, whereas in incontinent subjects, 13 produced only negative fatigue rates and 14 produced only positive fatigues or mixed results, suggesting that positive fatigue rates are more frequent in incontinent subjects (chi square test, p = 0.049).
Table 5.3 Results of pelvic floor strength and fatigue and anal manometry and fatigue in the 64 subjects over the age of 35 years. Annotation: VMSP, pelvic floor squeeze pressure; VFR1, 1\textsuperscript{st} measurement of pelvic floor fatigue; VTIIFR1, type II fatigue rate of 1\textsuperscript{st} pelvic floor fatigue measurement; VTIIdur1, duration of type II fatigue rate of 1\textsuperscript{st} pelvic floor fatigue measurement; VTIFR1, type I fatigue rate of 1\textsuperscript{st} pelvic floor fatigue measurement; VFR2, 2\textsuperscript{nd} pelvic floor fatigue measurement; VTIIFR2, type II fatigue rate of 2\textsuperscript{nd} pelvic floor fatigue measurement; VTIIdur2, duration of type II fatigue rate of 2\textsuperscript{nd} pelvic floor fatigue measurement; VTIFR2, type I fatigue rate of 2\textsuperscript{nd} pelvic floor fatigue measurement; VAUc1, area under the 1\textsuperscript{st} pelvic floor fatigue curve (random units); VAUc2, area under the 2\textsuperscript{nd} pelvic floor fatigue curve (random units); AMRP, anal maximum resting pressure; AMSP, anal maximum squeeze pressure; AFR1, 1\textsuperscript{st} anal fatigue measurement; AFR2, 2\textsuperscript{nd} anal fatigue measurement.

<table>
<thead>
<tr>
<th></th>
<th>Continent</th>
<th>Incontinent</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMSP (cmH\textsubscript{2}O)</td>
<td>27.17 ± 18.16</td>
<td>8.97 ± 12.88</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>VFR1 (cmH\textsubscript{2}O/min)</td>
<td>-17.69 ± 23.79</td>
<td>-4.93 ± 10.52</td>
<td>0.03</td>
</tr>
<tr>
<td>VTIIFR1 (cmH\textsubscript{2}O/min)</td>
<td>-224.59 ± 161.74</td>
<td>-172.77 ± 200.46</td>
<td>0.362</td>
</tr>
<tr>
<td>VTIIdur1 (seconds)</td>
<td>2.6 ± 1.9</td>
<td>2.3 ± 1.4</td>
<td>0.501</td>
</tr>
<tr>
<td>VTIFR1 (cmH\textsubscript{2}O/min)</td>
<td>-10.02 ± 22.18</td>
<td>-3.82 ± 12.09</td>
<td>0.269</td>
</tr>
<tr>
<td>VFR2 (cmH\textsubscript{2}O/min)</td>
<td>-14.93 ± 20.66</td>
<td>-2.88 ± 6.58</td>
<td>0.02</td>
</tr>
<tr>
<td>VTIIFR2 (cmH\textsubscript{2}O/min)</td>
<td>-243.56 ± 170.51</td>
<td>-138.61 ± 136.29</td>
<td>0.058</td>
</tr>
<tr>
<td>VTIIdur2 (seconds)</td>
<td>2.4 ± 1.5</td>
<td>2.1 ± 0.8</td>
<td>0.461</td>
</tr>
<tr>
<td>VTIIFR2 (cmH\textsubscript{2}O/min)</td>
<td>-9.42 ± 20.58</td>
<td>0.63 ± 3.71</td>
<td>0.056</td>
</tr>
<tr>
<td>VAUc1</td>
<td>3384 ± 2704</td>
<td>1319 ± 1233</td>
<td>0.004</td>
</tr>
<tr>
<td>VAUc2</td>
<td>3298 ± 2605</td>
<td>1239 ± 1446</td>
<td>0.005</td>
</tr>
<tr>
<td>AMRP (cmH\textsubscript{2}O)</td>
<td>72.08 ± 27.04</td>
<td>37.31 ± 24.2</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>AMSP (cmH\textsubscript{2}O)</td>
<td>105.62 ± 57.61</td>
<td>33.0 ± 28.88</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>AFR1(cmH\textsubscript{2}O/min)</td>
<td>-105.70 ± 92.58</td>
<td>-39.88 ± 102.19</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>AFR2 (cmH\textsubscript{2}O/min)</td>
<td>-88.57 ± 75.73</td>
<td>-21.38 ± 33.04</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>
Effect of parity of pelvic floor strength and fatigue

Among the continent subjects, seven were nulliparous, four were para 1, ten were para 2, three were para 3 and one was para 5. Among the incontinent subjects, one was nulliparous, five were para 1, thirteen were para 2, ten were para 3, two were para 4, and three were para 5. There was a significant difference between the proportions of continent and incontinent subjects who were parous or nulliparous (chi square test, $p = 0.005$).

There was a significant but weak negative correlation between parity and pelvic floor strength (Pearson correlation, $r = -0.477$, $p < 0.001$). Similarly there are weak but significant correlations between parity and $1^{\text{st}}$ pelvic floor fatigue rate ($r = 0.454$, $p = 0.002$) and $2^{\text{nd}}$ pelvic floor fatigue rate ($r = 0.349$, $p = 0.032$).

The pelvic floor strength and fatigability were compared between parous and nulliparous subjects and the results are shown in table 5.4. There was a significant difference in pelvic floor strength between parous and nulliparous subjects but the difference in fatigue rate was not significantly different. However, where both fatigue rate measurements were compared in an ANOVA, the difference in fatigue rate between parous and nulliparous women was significant ($p = 0.022$).

<table>
<thead>
<tr>
<th></th>
<th>Nulliparous (n = 8)</th>
<th>Parous (n = 47)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMSP (cmH$_2$O)</td>
<td>33.38 ± 23.32</td>
<td>13.49 ± 14.92</td>
<td>0.002</td>
</tr>
<tr>
<td>VFR1 (cmH$_2$O/min)</td>
<td>-32.26 ± 29.11</td>
<td>-7.08 ± 13.59</td>
<td>0.063</td>
</tr>
<tr>
<td>VFR2 (cmH$_2$O/min)</td>
<td>-19.75 ± 27.18</td>
<td>-6.61 ± 12.28</td>
<td>0.294</td>
</tr>
</tbody>
</table>

Table 5.4 Comparison of pelvic floor strength (VMSP) and $1^{\text{st}}$ and $2^{\text{nd}}$ fatigue rates (VFR1 and VFR2 respectively) in nulliparous and parous women.

Twenty three of the subjects had had a vaginal delivery but never required an instrumental delivery. Sixteen had had at least one instrumental delivery. The mean pelvic floor strength differed significantly between these groups (spontaneous vaginal delivery only: $18.48 \pm 16.99$ cmH$_2$O; at least one instrumental delivery: $7.13 \pm 8.79$ cmH$_2$O; t-test, $p = 0.017$) but the difference between the mean fatigue rates of those only delivered spontaneously ($-10.38 \pm$
16.99 and -8.02 ± 13.94 cmH₂O/min) and those delivered by at least one instrumental delivery (-1.74 ± 9.82 and -3.58 ± 13.13 cmH₂O/min) was not statistically significant.

**Relationship with anal manometry and fatigue**

All measures of anal manometry and fatigue (MRP, MSP, FR1 and FR2) were significantly different between continent and incontinent subjects: the anal resting and squeeze tone were lower in incontinent subjects and the fatigue rates were slower. Pelvic floor and anal canal fatigue rates also correlate moderately strongly but highly significantly (Pearson correlation, r values between 0.51 and 0.624, p ≤ 0.002). Subjects who have a positive pelvic floor fatigue rate are more likely to have a positive anal fatigue rate also (chi square, p = 0.007).

**Changes in the pelvic floor during pregnancy and after delivery in primigravid women**

**Pelvic floor strength and fatigue at booking**

Sixteen women underwent measurement of the pelvic floor strength and fatigue at booking. In a further two, measurements were attempted but unsuccessful because they were unable to retain the vaginal probe. Mean maximum squeeze pressure (VMSP) was 28 cmH₂O ± standard deviation 12.62 cmH₂O. The mean first fatigue reading (VFR1) was -20.19 cmH₂O/min ± 19.64 cmH₂O/min and mean second fatigue reading was -12.0 cmH₂O/min ± 16.61 cmH₂O/min. These are shown in table 5.5, along with the fatigue rates of the first steep part of the curve (type II fatigue rate) and second shallower part of the curve (type I fatigue rate).
Pelvic floor strength and fatigue later in pregnancy

Eleven women underwent measurement of the pelvic floor strength and fatigue later in the pregnancy. A further ten were unable to retain the vaginal probe and were therefore unable to complete the measurements. This was thought to be due to a low fetal head in four, low-lying placenta in three and polyhydramnios in one. The mean VMSP was $27.09 \pm 13.21$ cmH$_2$O, VFR1 was $-20.6 \pm 20.29$ cmH$_2$O/min and the VFR2 was $-17.37 \pm 17.46$ cmH$_2$O/min (see table 5.5).

Comparison of pelvic floor strength and fatigue between beginning and end of pregnancy

Five women completed two measurements of pelvic floor strength and fatigue during their pregnancy. There was no statistically significant difference in pelvic floor strength (paired t-test, $p = 0.514$) or fatigue rate (ANOVA, $p = 0.054$) between the two measurements, but numbers are too limited to provide robust analysis.

Pelvic floor strength and fatigue post partum

Seventeen women underwent measurement of pelvic floor strength and fatigue post partum. The mean VMSP was $23.53 \pm 14.52$ cmH$_2$O, VFR1 was $-7.53 \pm 10.27$ cmH$_2$O/min and VFR2 was $-5.94 \pm 6.85$ cmH$_2$O/min (see table 5.5).

Comparison of pelvic floor strength and fatigue before and after delivery

Pelvic floor strength and fatigue were measured at both beginning of pregnancy and post partum in eleven women. The VMSP was significantly lower after delivery (paired t-test, $p = 0.006$). VFR1 was significantly slower post partum than at booking ($p = 0.044$), but not VFR2 ($p = 0.236$). However, where both fatigue rates at each time point are compared in an ANOVA, there is a significant slowing in pelvic floor fatigue after childbirth ($p = 0.004$).
There was no significant difference between type II fatigue rate at beginning of pregnancy and post partum (VTII FR1, p = 0.935; VTII FR2, p = 0.108; paired t-test), nor between the type I FR from booking and post partum (VTIFR1, p = 0.243; VTIFR2, p = 0.428; paired t-test). Nor was there any difference when both measurements from each time point were compared in an ANOVA (type II FR, p = 0.225; type I FR, p = 0.102).

**Delivery details and impact on pelvic floor strength and fatigue**

Of the participants who underwent pelvic floor measurements post partum, ten had a spontaneous vaginal delivery, four required Ventouse assistance, two required forceps assistance and one delivered by emergency Caesarean section. There were no statistically significant differences in the pelvic floor strength (VMSP) or fatigue rate between those who had a spontaneous vaginal delivery and those who had instrumental assistance.
<table>
<thead>
<tr>
<th></th>
<th>Booking (n = 16)</th>
<th>Third (n = 11)</th>
<th>Post partum (n = 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMSP (cmH\textsubscript{2}O)</td>
<td>28.0 ± 12.62 (6 – 49)</td>
<td>27.09 ± 13.2 (7 – 46)</td>
<td>23.53 ± 14.52 (6 – 56)</td>
</tr>
<tr>
<td>FR1 (cmH\textsubscript{2}O/min)</td>
<td>-20.19 ± 19.64 (-53.16 – 16.38)</td>
<td>-20.6 ± 20.29 (-55.32 – 2.28)</td>
<td>-7.53 ± 10.27 (-25.08 – 12.48)</td>
</tr>
<tr>
<td>TIIFR1 (cmH\textsubscript{2}O/min)</td>
<td>-212.37 ± 147.61 (-555.96 – -49.02)</td>
<td>-295.23 ± 182.84 (-625.2 – -126.18)</td>
<td>-318.93 ± 317.88 (-1045.38 – -31.2)</td>
</tr>
<tr>
<td>TIFR1 (cmH\textsubscript{2}O/min)</td>
<td>-133.41 ± 26.50 (-87.54 – 18.90)</td>
<td>-11.57 ± 13.95 (-29.76 – 7.20)</td>
<td>-2.31 ± 10.65 (-19.74 – 19.14)</td>
</tr>
<tr>
<td>AuC1</td>
<td>3091 ± 1524 (207 – 7250)</td>
<td>2732 ± 1505 (341 – 5197)</td>
<td>3412 ± 2208 (388 – 7879)</td>
</tr>
<tr>
<td>FR2 (cmH\textsubscript{2}O/min)</td>
<td>-12.0 ± 16.61 (-36.42 – 18.3)</td>
<td>-17.37 ± 17.46 (-47.58 – 6.54)</td>
<td>-5.94 ± 6.85 (-18.96 – 6.48)</td>
</tr>
<tr>
<td>TIIFR2 (cmH\textsubscript{2}O/min)</td>
<td>-308.85 ± 189.02 (-763.62 – -114.36)</td>
<td>-295.62 ± 99.27 (-449.1 – -189.2)</td>
<td>-369.65 ± 354.74 (-1298.04 – -51.24)</td>
</tr>
<tr>
<td>TIFR2 (cmH\textsubscript{2}O/min)</td>
<td>-4.35 ± 14.60 (-30.24 – 18.60)</td>
<td>-9.04 ± 7.39 (-21.84 – 0.05)</td>
<td>-0.025 ± 6.22 (-15.54 – 8.10)</td>
</tr>
<tr>
<td>AuC2</td>
<td>2820 ± 1642 (190 – 6726)</td>
<td>2873 ± 885 (2113 – 4368)</td>
<td>3134 ± 1857 (167 – 7053)</td>
</tr>
</tbody>
</table>

Table 5.5 Mean ± standard deviation (range) of pelvic floor strength (VMSP) and fatigue rates from booking, third trimester and post partum in primigravid women. Annotation: FR1, overall fatigue rate of 1\textsuperscript{st} measurement; TIIFR1, type II fatigue rate of 1\textsuperscript{st} fatigue measurement; TIFR1, type I fatigue rate of 1\textsuperscript{st} fatigue measurement; AuC1, area under curve of 1\textsuperscript{st} fatigue measurement (random units); FR2, overall fatigue rate of 2\textsuperscript{nd} measurement; TIIFR2, type II fatigue rate of 2\textsuperscript{nd} fatigue measurement; TIFR2, type I fatigue rate of 2\textsuperscript{nd} fatigue measurement; AuC2, area under curve of 2\textsuperscript{nd} fatigue measurement (random units).
Discussion

Findings

It was found that as subjects aged, the pelvic floor strength reduced. It is known that muscle strength is lost with age. This is because of both generalised loss of skeletal muscle bulk\textsuperscript{115} and reduced contraction force generated by individual muscle fibres.\textsuperscript{116} This inverse relationship between age and pelvic floor strength was found in a study of the clinical assessment of pelvic floor strength.\textsuperscript{117} Similar findings have been shown in the anal canal – both resting tone and squeeze tone have been shown to fall with age.\textsuperscript{27,86,118,119} There are also changes in the appearance of anal sphincters on endoanal ultrasound scanning with age.\textsuperscript{26,60}

The pelvic floor strength was lower in incontinent women than in continent women. This has previously been shown in cases of faecal incontinence\textsuperscript{83} and stress urinary incontinence,\textsuperscript{120} and is in keeping with other differences in the pelvic floor of incontinent subjects – lower pressures are found in the anal canal in incontinent patients.\textsuperscript{57} It would seem that reduced PFM strength is causative in the development of incontinence, rather than co-incidental, because studies have shown that increasing PFM strength can improve both faecal and stress urinary incontinence.\textsuperscript{83,121}

This study found a slower PFM fatigue rate in incontinent women, in comparison with studies showing no difference in fatigability of the PFM of subjects with and without faecal incontinence\textsuperscript{83} or stress urinary incontinence.\textsuperscript{76} Published studies of the fatigability of the EAS in subjects with FI have shown a reduced fatigue rate index, a measure of both EAS strength and fatigue, but no difference in fatigue rate,\textsuperscript{80,81} whereas others have shown no difference in either fatigue rate or fatigue rate index.\textsuperscript{122} However, the methodology of this last study can be questioned because incontinent subjects were compared with patients with constipation, rather than continent controls, and used a 10 second squeeze with pull-through technique, rather than a 20 or 40 second squeeze after
identifying the high pressure zone of the anal canal. Previous work in this group has shown differences in the fatigue rate, but not the fatigue rate index, between continent and incontinent women.\textsuperscript{102}

As with the measurement of anal fatigue, some subjects produced a positive PFM fatigue rate, i.e. the pressure rose with time rather than falling as is expected with the effect of fatigue on sustained skeletal muscle contraction. Positive fatigue rates were more common in sustained PFM contractions than sustained EAS contractions: 34\% of pelvic floor contractions were positive, compared with 17\% of EAS fatigue measurements (see chapter 3: Reproducibility), although subjects with a positive PFM fatigue rate were more likely to have a positive EAS fatigue rate. Some of the EAS fatigue rates were positive because of an inability to sustain the prolonged contraction and others were because of the subject straining rather than squeezing (see figure 3.4). However, this did not appear to be the case with pelvic floor contraction. Straining was visualised by the observer: either the vaginal probe became dislodged or it did not move forward and inwards as occurs on correct contraction of the pelvic floor, and “poor technique” was documented rather than recording a pelvic floor strain. Examples of positive fatigue rates can be seen in Appendix 4, especially participants ID3, 6 and 16. The cause of a rising pressure during a sustained voluntary PFM contraction has not been established in this study. As discussed in Chapter 3, page 60, EMG analysis of the contraction would allow further investigation of positive fatigue rates, either EAS or PFM, to establish whether motor unit recruitment could account for this finding in a proportion of subjects.

Incontinent subjects in this study were more likely to be parous, which is in keeping with the known relationship between vaginal delivery and pelvic floor disorders.\textsuperscript{88} There was a correlation between pelvic floor strength and parity, also in keeping with the study by Kisli \textit{et al} describing the decreasing EMG activity of PFM with increasing parity.\textsuperscript{39} Pelvic floor fatigue rate also correlated with parity, a novel finding. Given these findings, the difference in pelvic floor strength and fatigue rate between nulliparous and parous women in this study is also unsurprising, but should perhaps be interpreted with caution, given the very
unequal group sizes in the comparison. Pelvic floor strength was lower in those who had had at least one instrumental delivery, and although the fatigue rate in these women was also slower, this difference was not statistically significant. Forceps delivery has previously been shown to affect pelvic floor strength\textsuperscript{45} and integrity.\textsuperscript{123}

The differences in anal manometry and fatigue between continent and incontinent women in this study fit with the literature.\textsuperscript{57,102} The highly significant difference in anal manometry and fatigue between the continent and incontinent subjects lends weight to the acceptance of a significant difference in pelvic floor strength and fatigue as well. The pelvic floor and anal fatigue rates correlated significantly, but the pelvic floor fatigue rate was slower than the anal fatigue rate, as also reported by Fernández-Fraga \textit{et al.}\textsuperscript{83} A slower pelvic floor fatigue rate suggests a greater resistance to fatigue and possibly a greater proportion of type I muscle fibres. Studies of the composition of pelvic floor musculature in humans report a similar preponderance of type I muscle fibres in the EAS, puborectalis and levator ani of both incontinent and continent subjects,\textsuperscript{124} although specific mention is made of predominance of type I fibres in the levator ani of incontinent subjects, which is not made in the description of EAS or puborectalis, suggesting a greater proportion of type I fibres in this muscle compared with the other two not seen in a later study.\textsuperscript{51}

Significant falls were seen in both pelvic floor strength and fatigability after childbirth, in contrast to findings in the EAS. Since vaginal delivery causes stretching of the PFM, and every effort is made to avoid overt damage to the EAS, this is perhaps not surprising. This is also in keeping with the known effects of labour on the pelvic floor. The pubococcygeus muscle is stretched by over three times its resting length during vaginal delivery\textsuperscript{125} and it is estimated that forces of 120 Newtons are exerted on the pelvic floor during the second stage of labour.\textsuperscript{123}
Method used

The use of a vaginal probe has been shown to be a reliable means of measuring pelvic floor muscle strength.\(^\text{108}\) Patient position affects pressures recorded by pelvic floor contraction.\(^\text{126}\) The left lateral position was therefore chosen to allow comparison with anal manometry results. Intravaginal pressure changes with alterations in intra-abdominal pressure and rises with contraction of other muscle groups, including gluteal and hip adductor muscles.\(^\text{127}\) A significant proportion of women are unable to correctly identify and contract their pelvic floor muscles.\(^\text{10;128}\) Therefore, correct pelvic floor contraction was confirmed by observing a pelvic floor lift as well as a rise in pressure.\(^\text{10}\)

The measurement of resting pressure of the pelvic floor muscles depends on a good fit of the vaginal probe within the levator hiatus. The levator hiatus varies in size between women, depending on parity.\(^\text{10;33}\) Instructions accompanying the Peritron state that air may have to be inflated into the vaginal probe, to give a good fit in some women. There is also constant baseline activity in the levator ani muscle.\(^\text{125}\) Therefore only the increment in pressure on voluntary contraction was measured.

The duration of squeeze that the levator ani can generate has not been documented in the literature. Pelvic floor physiotherapists encourage women to hold a contraction for 10 seconds during pelvic floor muscle training.\(^\text{128}\) A voluntary contraction of the EAS cannot be maintained for much more than 1 to 2 minutes.\(^\text{75}\) In their assessment of EAS fatigue, Marcello et al asked participants to contract their EAS for 40 seconds.\(^\text{80}\) In our group, participants found 40 seconds uncomfortably long and we have therefore been using 20 seconds.\(^\text{81}\) Given that no duration of levator contraction has been documented, the same protocol of two prolonged contractions maintained for 20 seconds, separated by a 2 minute rest period, was used for assessment of pelvic floor fatigue also. Since pelvic floor fatigue rate is slower than EAS fatigue rate, it may be that fatigue of the pelvic floor was not recorded during a 20 second squeeze. Since it is not possible to voluntarily contract a single portion of the PFM without contracting the whole pelvic floor,\(^\text{129}\) it was decided to use the
same technique as used for measurement of EAS fatigue, for which a 20 second squeeze is used because 40 seconds was found too uncomfortable by previous study participants. It was found that PFM fatigue rate is slower than EAS fatigue rate. It may be, then, that fatigue of the pelvic floor was not recorded during a 20 second squeeze and further work to develop this test should include sustained voluntary contractions of greater lengths.

Work is also required to establish the length of rest period required between repeated measures of pelvic floor fatigue. In this study the second measure of pelvic floor fatigue was significantly slower than the first, suggesting that the two minute rest period was insufficient to allow the PFM to recover. There is no such difference between repeated anal fatigue measures (see Chapter 3: Reproducibility), suggesting that the two minute rest period was sufficient for recovery of the EAS. However, if the PFM has a slower fatigue rate and is therefore more fatigue resistant, why does it appear to require a longer recovery period?

Conclusion

This study has shown that it is possible to measure pelvic floor pressure and fatigue rate and that these differ between continent and incontinent women. However, further work is required to determine the usefulness of this test definitively. Work is required not only in establishing appropriate duration of voluntary contraction and rest period between repeated contractions, but also in developing normal ranges for each age group.

The study aimed to determine if the measurement of PFM strength and fatigue would be useful in the routine clinical assessment of patients with FI, by comparing pelvic floor strength and fatigue in continent and incontinent women and by determining the effect of childbirth on PFM strength and fatigue. The study has described the difference between continent and incontinent women and the effect of childbirth on PFM strength and fatigue, but it is not clear whether measurement of PFM strength and fatigue is useful in clinical practice.
Summary

This study showed that pelvic floor strength falls with age, is lower in incontinent women, who also have slower pelvic floor fatigue rate. Positive fatigue rates are more common in incontinent women. The pelvic floor strength of parous women is lower than in nulliparous women and fatigue rate may also be reduced. Pelvic floor strength and fatigue are reduced post partum.
6. Cephalopelvic disproportion
It has been observed that the onset of FI is related to childbirth,\textsuperscript{34-36} is more common after the vaginal delivery of bigger babies and after instrumental delivery,\textsuperscript{2} that Caesarean section delivery appears to be protective,\textsuperscript{84} and anal sphincter morphology and function do not alter after Caesarean section,\textsuperscript{111} in comparison with significant numbers of sphincter defects after vaginal delivery.\textsuperscript{32} Not only does fetal size vary, but also maternal pelvis size. Cephalopelvic disproportion (CPD) is where there is disparity between fetal head size and maternal pelvis size, resulting in either inability or difficulty to deliver vaginally.\textsuperscript{93} We wished to determine if measuring CPD could predict changes in pelvic floor symptoms post partum or alteration in pelvic floor measurements.

\textbf{Method}

Using 3.5MHz ultrasound probe, the anteroposterior (AP) diameter of the pelvis was measured transabdominally using the technique described by Katanosaka \textit{et al.}\textsuperscript{90} measuring from the superoposterior edge of the symphysis pubis to the sacrum – identified as the last identifiable bright echo in the depth of field.

CPD was measured in primigravid women taking part in the study of changes in pelvic floor function during pregnancy and after delivery, and in non-pregnant women undergoing magnetic resonance imaging (MRI) pelvic scanning for perianal fistulae, in order to determine the accuracy of ultrasound (US) measurements by comparison with MR measurements.

\textbf{Participants}

US pelvimetry was measured in fifteen women (mean age 30.87 years, standard deviation 4.44 years) taking part in the study of changes in the pelvic floor during pregnancy and after delivery. Two measurements were obtained in ten of these women. In five, the measurement was obtained post partum. Five non-pregnant women underwent US pelvimetry in order to compare US and MR measurement of the pelvis.
Ultrasound pelvimetry results

The mean (± standard deviation) AP diameter of the pelvis measured by ultrasound was 14.95 (± 1.50) cm on first measurement and second measurement was 14.13 (± 1.58) cm. The US pelvimetry measurement ranged between 11.42 and 17.78 cm. Full details of the repeatability of US pelvimetry and comparison between US and MR pelvimetry are given in Chapter 3: Reproducibility. This found that the US measurement was repeatable with a repeatability co-efficient of 1.25 cm. Therefore, in all further statistical analysis, only the first measurement of US pelvimetry is used.

The US pelvimetry measurement was divided by the neonatal head circumference in order to estimate CPD. This was termed the cephalopelvic ratio (CPR), had a mean of 0.429 and ranged between 0.36 and 0.57.

Effect of ultrasound pelvimetry on labour and delivery

No effect on delivery was found of either the US pelvimetry measurement or cephalopelvic disproportion as measured in the CPR. There was no correlation between US pelvimetry or CPR and length of 2\textsuperscript{nd} stage of labour, nor was there any difference between mean US pelvimetry of those four with shorter than average 2\textsuperscript{nd} stage of labour (14.61 ± 1.48 cm) and those nine with longer 2\textsuperscript{nd} stage of labour (15.09 ± 1.68 cm; t-test, \( p = 0.629 \)). When neonatal head circumference was included in the analysis by comparing CPR with labour length, again no difference is found (long 2\textsuperscript{nd} stage labour, mean CPR 0.436 ± 0.069 cm\(^{-1}\), vs. shorter 2\textsuperscript{nd} stage of labour, mean CPR 0.409 ± 0.034 cm\(^{-1}\); t-test, \( p = 0.48 \)).

Five had a spontaneous vaginal delivery (SVD), six delivered by Ventouse, two by Forceps and one by emergency Caesarean section. One was missing to follow up. There was no difference in mean US pelvimetry between those delivered by SVD (14.89 ± 1.49 cm) and those who required instrumental or Caesarean delivery (15.08 ± 1.65 cm; t-test, \( p = 0.83 \)). And again, there is no difference between CPR of those delivering spontaneously (0.402 ± 0.045 cm\(^{-1}\)) and those requiring assistance (0.441 ± 0.061 cm\(^{-1}\); t-test, \( p = 0.476 \)).
Relationship between ultrasound pelvimetry and anal manometry and fatigue

The post partum anal manometry results in the eleven women who underwent ultrasound pelvimetry and for whom postpartum measurements are available are shown in table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Disproportionate (n = 7)</th>
<th>Adequate (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRP (cmH₂O)</td>
<td>Mean ± standard deviation 76.14 ± 18.38</td>
<td>94.0 ± 18.82</td>
</tr>
<tr>
<td></td>
<td>Median (range)            76.0 (48 – 102)</td>
<td>96.5 (69 – 114)</td>
</tr>
<tr>
<td>MSP (cmH₂O)</td>
<td>Mean ± standard deviation 132.71 ± 103.39</td>
<td>132.73 ± 76.19</td>
</tr>
<tr>
<td></td>
<td>Median (range)            75.0 (61 – 324)</td>
<td>152.5 (29 – 197)</td>
</tr>
</tbody>
</table>

Table 6.2 Anal maximum resting pressure (MRP) and maximum squeeze pressure (MSP) in those with a small maternal pelvis to neonatal head size ratio (disproportionate) and those with a good maternal pelvis to neonatal head ratio (adequate).
The changes in MRP, MSP, FR1 and FR2 between measurements taken during pregnancy and those taken after delivery were calculated in order to determine if CPD had any differing effect on the change in anal manometry or fatigue. There were no differences in the change in anal manometry or fatigues between those with a disproportionate or adequate CPR. There were also no differences between the post partum type I and II fatigue rates, fatigue rate indices, or areas under the fatigue curves between those with disproportionate and adequate CPR.

**Relationship between ultrasound pelvimetry and pelvic floor strength and fatigue**

The post partum pelvic floor pressure and fatigue results in the ten women who underwent ultrasound pelvimetry and for whom postpartum measurements are available are shown in table 6.3.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
<th>Mean ± standard deviation</th>
<th>Median (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMSP (cmH₂O)</td>
<td>Mean ± standard deviation</td>
<td>22.2 ± 17.15</td>
<td>15.5 (6 – 26)</td>
</tr>
<tr>
<td>VFR1 (cmH₂O/min)</td>
<td>Mean ± standard deviation</td>
<td>-6.20 ± 12.11</td>
<td>-4.77 (-25.08 – 12.48)</td>
</tr>
<tr>
<td>VFR2 (cmH₂O/min)</td>
<td>Mean ± standard deviation</td>
<td>-4.09 ± 5.38</td>
<td>-5.16 (-11.64 – 6.48)</td>
</tr>
</tbody>
</table>

**Table 6.3** Post partum pelvic floor strength (VMSP) and fatigue rates (VFR1 and VFR2) in the ten subjects who underwent both ultrasound pelvimetry and post partum pelvic floor strength and fatigue measurements.

Although there were no statistically significant differences between the pelvic floor strength or fatigue rates post partum in those with disproportionate or adequate pelvises (see table 6.4), the pressures are lower in those with a disproportionate pelvis and the lack of statistical significance may reflect the small numbers available for analysis.
Table 6.4 Pelvic floor strength (VMSP) and fatigue rates (VFR1 and VFR2) post partum in the nine subjects for whom ultrasound pelvimetry and post partum pelvic floor measurements were available.

Relationship between ultrasound pelvimetry and pelvic floor symptoms

There was no difference between the post partum Vaizey, MHQ or KHQ of those with disproportionate pelvis ratio and those with adequate ratio, nor were there any correlations between US pelvimetry and symptom severity scores.

Discussion

Findings

US pelvimetry was found to range between 11.42 and 17.78 cm in this small group of Caucasian, British women. When the US measurement was compared with MR, it was found to agree to within 4.26 cm in 95% of cases (see Chapter 3: Reproducibility). This degree of inaccuracy is probably unacceptable, given the relatively small range of measurements obtained. However, accuracy of US measurements may be improved by ensuring that subjects have a full bladder. This is an area for future development of the test.

The size of maternal pelvis did not appear to affect labour or mode of delivery. Nor were any statistically significant effects on anal manometry or fatigue rate found, although the MRP was higher in those with an “adequate” pelvis than in those with a “disproportionate” pelvis. This is in keeping with the finding of
higher MRP post partum in the study of anal manometry and fatigue rate in primigravid women. Again, lower pelvic floor strength and slower pelvic floor fatigue rates were found in women with disproportionate pelvis to neonatal head ratio than in those with adequate pelvises, although this was not statistically significant. Numbers of participants in the study are small, which may explain the lack of statistically significant findings.

Cephalopelvic ratio did not affect symptom severity scores or pelvic floor symptom-specific quality of life. This is not unexpected, because no differences were found in symptoms before and after delivery, as reported in Chapter 4. As also discussed in chapter 4, studies which have found an effect of delivery on symptoms have included much greater numbers of participants. 35-38

The study can be criticised for the inadequate number of participants, possibly resulting in a lack of statistically significant findings. The criticism is justified, but recruiting primigravid women to the study was difficult, as outlined in Chapter 4, and finding time for the senior ultrasonographer to carry out the scans in the very busy antenatal ultrasound department was challenging, even though the scan itself was very brief. A much larger study, involving the routine measurement of US pelvimetry by all antenatal ultrasonographers and the collection of delivery data and pelvic floor symptoms post partum might be a way of including the majority of primigravid women and determining the effect of US pelvimetry on labour, delivery and pelvic floor symptoms, but would require the enthusiasm and participation of a large number of staff within the antenatal department.

**Method**

CPD can be measured clinically or radiologically, but radiological assessments are presumed to be more accurate. 91 Radiological assessments can make use of plain X-rays, CT, MRI or US. Exposure of the unborn child to X-rays is associated with increased risk of cancers 130 and MR is limited by expense and availability of scanners. It has been shown that US can be reliably used to
measure pelvimetry,\textsuperscript{90} and as the use of US is safe in pregnancy, cheap and widely available we used this method to measure pelvimetry in our study.

US pelvimetry is limited because it can only measure one diameter of the three-dimensional pelvis. Complete pelvimetry involves the measurement of the anteroposterior pelvic inlet diameter (between the symphysis pubis and sacral promontory), the transverse pelvic inlet diameter (between arcuate lines of the iliac bones) and the interspinous distance between the iliac spines,\textsuperscript{131} whereas US pelvimetry only measures the distance from the symphysis pubis to the S3 promontory. A woman with an anthropoid shape pelvis\textsuperscript{8} would therefore have a normal measurement on US pelvimetry, and the limited size would not be reflected in the measurement. It is unknown how this relates to the effect of vaginal delivery on the pelvic floor. The US measurements are also more accurate in a woman with a full bladder.

\textbf{Future work}

The criticism of previous studies of the potential protection that Caesarean section may provide against the development of FI, was the inadequate follow up\textsuperscript{85} or numbers studied.\textsuperscript{84} For US pelvimetry to be potentially useful in the antenatal estimation of postnatal pelvic floor trauma, longer term follow up is required, studying both continent and incontinent women. This could be studied in a retrospective study of cephalopelvic disproportion, measuring pelvimetry in symptomatic women and continent, age-matched controls and collecting obstetric data from delivery units. Pelvis size and shape do not change in an adult unless as a result of trauma or bony disease (e.g. Paget’s disease), so can be assessed at any point in adult life. Pelvimetry could be measured using a low dose CT protocol\textsuperscript{130} in order to give all three diameters of the pelvis, rather than limiting the examination by using US. Obstetric data are routinely kept for 25 years from delivery date, making it possible to accurately study women for up to 25 years from their first delivery. Neonatal birth weight and head circumference would be pertinent to the study. Women are able to recall the other significant data, e.g. route of delivery, extent of perineal trauma. Analysis of the cephalopelvic disproportion that existed might then lead to
understanding of a safe maternal pelvis to fetal head ratio at which future development of FI was unlikely.

Summary

This study confirms that the AP diameter of the pelvis can be measured in our population, with good repeatability, although accuracy when compared with MR is still questionable. However, we have not demonstrated an effect of cephalo-pelvic disproportion on anal manometry, fatigue, pelvic floor strength or fatigue, nor on the progress of labour and route of delivery, nor the development of symptoms post partum. This may be due to inadequate subject numbers.
7. Discussion
Our theory of the pathophysiology of idiopathic faecal incontinence is that childbirth causes damage to the innervation of the pelvic floor musculature,\textsuperscript{15} including the innervation of the external anal sphincter.\textsuperscript{21} This injury causes a selective loss of type II muscle fibres, resulting in reduced squeeze pressure. Reinnervation causes fibre type grouping\textsuperscript{51} when previously type II muscle fibres start synthesising the slow-myosin isoform, becoming type I muscle fibres. This is manifest in a slowing in the fatigue rate and a reduction in strength. Subsequent events, e.g. the menopause,\textsuperscript{29} aging,\textsuperscript{27} result in further weakening of the anal sphincters and symptomatic incontinence.

There is evidence for some of the steps in this theory, but not all. Some evidence is circumstantial – effects are measured, but the cause for the effects has not been established definitively. Therefore, in order to help fill in some of these gaps in the evidence, this study was carried out, with the aim of determining the following:

- The changes in anal manometry and fatigue as a result of childbirth and the effect of different delivery routes on these.
- Any differences in pelvic floor strength and fatigue between continent and incontinent women and whether these are affected by childbirth.
- Whether ultrasound pelvimetry can predict the degree of change in anal or pelvic floor strength or fatigue after childbirth.

In summary, this work has shown changes after childbirth in the muscular elements of the pelvic floor, both pelvic floor diaphragm and the anal sphincters. The pilot study showed a reduction in the ability to produce a maximal voluntary contraction of the external anal sphincter, although this was not confirmed by the current study. The pilot study also demonstrated that the EAS was more resistant to fatigue post partum, again not confirmed by the current study. A significant difference between the strength and resistance to fatigue of the pelvic floor musculature of continent and incontinent women was shown, with evidence that changes in pelvic floor muscle strength and fatigue also occur as a result of childbirth. No effect of different delivery routes was measured on anal manometry or fatigue or pelvic floor strength or fatigue. This may be due
to small numbers of participants. Measurement of ultrasound pelvimetry, although possible in our patient population, has not been shown to be useful in predicting the degree of injury to the pelvic floor, possibly due to inadequate study size.

**Measured parameters**

The pelvic floor is a complex organ, with three distinct components (muscles, their innervation and connective tissue supporting structures) and varied roles, from maintenance of continence to sexual functions and significant alteration during parturition. In order to understand dysfunction of the pelvic floor, measurement of its function must be carried out correctly and what the measurements reflect must be understood.

**Fatigue rate**

It can be argued that fatigue rate is another function of maximum squeeze pressure and that it gives no more information than the squeeze pressure already gives. If this were so, strength and fatigue rate would correlate strongly and significantly. However, anal MSP correlates only moderately strongly with fatigue rate (Pearson correlation: FR1, $r = -0.634$, $p < 0.001$; FR2, $r = -0.528$, $p < 0.001$) although pelvic floor strength correlates more strongly with fatigue rate (Pearson correlation: VFR1, $r = -0.803$, $p < 0.001$; VFR2, $r = -0.723$, $p < 0.001$). Therefore, the differences seen in fatigue rate are likely to be true alterations in muscle physiology and worth investigating, not an indirect measure of muscle strength.

**Area under the fatigue curve**

The fatigue rate index (FRI) of sustained voluntary anal contraction is not significantly different between continent and incontinent subjects in this study (Wilcoxon signed ranks test; FRI1, $p = 0.32$; FRI2, $p = 0.147$; ANOVA comparing both FRI between continent and incontinent subjects, $p = 0.523$).
This is in contrast to previous published work on the FRI\textsuperscript{80,81} but is in agreement with previous work by this group.\textsuperscript{102} The calculation of the FRI combines maximum squeeze pressure and fatigue rate in an easy calculation and estimates the length of time that a contraction can be sustained. The relationship between FRI and the area under the fatigue curve (AuC) was examined. These do not correlate (Spearman’s correlation, $r = 0.139$, $p = 0.067$). AuC is significantly different between continent and incontinent subjects (Wilcoxon signed ranks test; AuC1, $p < 0.001$; AuC2, $p < 0.001$; ANOVA comparing both AuC between continent and incontinent subjects, $p < 0.001$).

The AuC measurement is a more accurate measure of how well a subject can sustain a pressure rise above baseline. Fatigue rate is calculated from a best-fit linear line, and FRI is also based on this best-fit line. However, AuC actually measures how long and by how much a subject can sustain a pressure rise. Unfortunately results cannot be compared between different centres: the results are highly dependent on the equipment and software used, especially the rate at which pressure readings are recorded. In order to make results more comparable across centres, it would be possible to sum a selection of the pressure readings. For example, if one centre were recording pressures at a rate of ten per second, we could calculate comparable AuC measurements by only summing one in three pressure readings recorded. This would also be a way that AuC measurements from the EAS contraction could be compared with the PFM contraction.

It would be interesting to investigate further what FRI or AuC are actually measuring. Could either of these reflect the bulk of the muscle in question? Further work involving both fatigue measurement and imaging might start to explore this relationship. Three-dimensional ultrasound scanning of the pelvic floor could be employed, especially as transvaginal imaging of the anal sphincter complex does not cause distraction of the muscle, potentially altering its measurable bulk.
Pelvic floor strength and fatigue

This study has shown that it is possible to measure pelvic floor fatigue, that this is an easy technique with a low test-retest bias. Patient acceptability was not specifically measured, but instrumentation of the vagina is more common than anal canal instrumentation and acceptable in the British culture, especially after the introduction of the cervical cancer screening programme. The changes in the pelvic floor musculature measured in incontinent women are of the same nature as the changes measured in the external anal canal. In a group of women with “idiopathic” FI, this is unsurprising – the triggering insult of childbirth in the majority affects the entirety of the pelvic floor. It would be interesting to repeat the comparison of pelvic floor strength and fatigue in a group with isolated anal disease, e.g. nulliparous women with anorectal Crohn’s or iatrogenic FI post haemorrhoidectomy or a Lord’s stretch.

It could be argued that since the alterations in PFM strength and fatigue measured are similar to those found in EAS strength and fatigue in women with FI, measurement of the PFM gives no additional information, the injury pattern recorded is the same. However, these are distinctive and different muscle groups which may work in a co-ordinated fashion but have been measured separately and the fatigue rate in both may be significantly slower in incontinent women than continent women, but the fatigue rate of the PFM is significantly slower than that of the EAS, suggesting that the PFM has a different nature. The difference in fatigue rate is not secondary to the measuring technique – although pressure measurements were less frequent in the measurement of PFM fatigue, the gradient of the graph obtained was then multiplied by the appropriate conversion constant (the number of data points per minute) to obtain a fatigue rate in cmH₂O/min which can be compared with other rates measured in cmH₂O/min.

PFM strength and fatigue rate were significantly reduced at 6 months post partum compared with antenatal values, whereas the measured changes in anal manometry at 11 weeks post partum were no longer significantly different by 6 months post partum. This would suggest that either the PFM recovers
more slowly, or that they sustain a more significant injury. There are a number of possible reasons for this. It could be an anomaly in the study design, that the measurements were not timed to reveal the recovery that the PFM are undergoing, and that if the PFM strength and fatigue were measured repeatedly post partum, or if the one post partum measurement was made later, recovery in the PFM strength and fatigue would be demonstrated. However, this does not explain why the EAS appears to recover more quickly than the PFM. The PFM are more centrally placed within the pelvic floor and are subject to significant stretching during vaginal delivery, and are therefore at more risk than the EAS during uncomplicated childbirth. The measured differences in EAS and PFM strength and fatigue rate may reflect this differing risk of injury and therefore the different injuries sustained. However, even in the primigravid women in this study who had not sustained previous damage to their pelvic floor, the PFM fatigue rate was significantly slower than the EAS fatigue rate. This may indicate that the muscle fibres of the PFM, or their innervation, are different in nature from that of the EAS. Although both the EAS and PFM have a preponderance of type I muscle fibres, it may be that the proportions of type I and II muscle fibres differ more significantly than was thought from these older histochemical studies.

The measurement of PFM strength and fatigue must be studied further before it can be universally accepted or introduced into clinical practice. The degree of intra-individual variability has been described in this study, but good inter-observer repeatability must also be established. Studies measuring repeatability of PFM fatigue measurements with different rest periods between repeated measures would also be useful, given the statistically significant difference between the 1\textsuperscript{st} and 2\textsuperscript{nd} measurements of PFM fatigue. Before introduction into clinical assessment, the normal range for PFM strength must be identified. However, as there is a negative correlation between PFM strength and age, normal ranges must be established for each age bracket.

Further studies are also required to establish the best method for measuring PFM fatigue rate. Repeated fatigue measurements with different lengths of voluntary contraction should be carried out, to ensure that the muscle has
started to fatigue. The duration of contraction that a muscle can sustain varies depending on the muscle in question. Therefore, fatigue studies must be adapted to the muscle in question. The duration of contraction that the PFM can sustain has not been established in this study, nor has it been reported in the literature. The ability to maintain a 20 second contraction, and the number of positive fatigue rates measured, may, therefore, reflect the ability of the PFM to sustain a longer contraction, and pelvic floor fatigability during 40 second and longer contractions would be useful to confirm or refute the fatigability of the PFM reported here.

Techniques employed

A lot of the variability seen in anal and pelvic floor squeeze pressure and fatigue rate is likely to be due to alterations in volition of the subject. One way of reducing this variability and studying true muscle strength and fatigue would be to study the pressure of a stimulated muscle over a time period. Feasibility studies to measure changes in anal canal pressure as a result of maximal S3 nerve root stimulation (during the insertion of sacral nerve stimulators for FI) found no increase in anal canal pressure, nor any increases in pelvic floor pressure. Direct stimulation of the pudendal nerve, as occurs during measurement of the PNTML, would be another potential route for the direct stimulation of the EAS. Modification of the probe used in the measurement of PNTML, with the incorporation of a pressure transducer in the region of the probe which lies within the anal high pressure zone, might allow stimulated EAS fatigue to be studied more “accurately”, reducing the some of the variability seen in voluntary contractions.

Measurement of stimulated muscle would certainly allow more solid conclusions about the nature of the muscle and its constitution to be made. If the aim is to identify the pathophysiology of the muscle injury, the resultant alterations in muscle fibre type proportions and to determine if the measurement of fatigue rate is an accurate way of measuring these changes, then a technique which eliminates central sources of fatigue and allowed neuromuscular factors only to be studied would be useful.
However, it can be argued that the voluntary contraction of the EAS and pelvic floor is what allows subjects to defer defaecation, so anything which detracts from the ability to contract the EAS at will, including lack of central awareness of correct pelvic floor muscle contraction, is important clinically and should therefore be included in a clinical study of FI. It has also been shown that electrical stimulation of the pelvic floor is not as effective as an exercise regime in improving pelvic floor strength and stress urinary incontinence. The central component of initiating muscle contraction is therefore important in increasing muscle strength and improving continence.

**Study aims**

Some of the specific aims of the study were met:

- Does childbirth alter anal fatigue rate?
  Although the pilot study answered this question, the current study did not confirm the findings. However, the current study was designed to take into account recovery in the pelvic floor and it may be that no changes in the voluntary contraction of the EAS were measured because complete recovery of the muscle and its innervation had occurred. A larger study, with repeated measures post partum, should answer this question, but recruiting adequate participant numbers would be difficult.

- Does the pelvic floor muscle fatigue rate differ between continent and incontinent women? Does childbirth alter pelvic floor fatigue?
  A significant difference in both the PFM strength and fatigue rate was shown between continent and incontinent women. PFM strength and fatigue rate are significantly lower in parous women, compared with nulliparous women, and both are lower post partum when compared with antenatal values.

- Does the route of delivery affect changes in anal or pelvic floor fatigue?
  The pelvic floor strength was significantly higher in women who had only ever had spontaneous vaginal delivery, compared with those who had required at
least one instrumental delivery, but the difference in PFM fatigue rates between these groups was not statistically significant. This retrospective analysis would suggest that instrumental delivery has a detrimental impact on PFM strength. However, in the prospective study, insufficient numbers delivered by Caesarean section were included in order to determine if those delivered by Caesarean were protected from alteration in the EAS or PFM fatigue rate. No delivery related factors (length of 2nd stage of labour, instrumental delivery, perineal trauma or episiotomy) were found to cause a significant difference in EAS or PFM strength or fatigue.

This aim has therefore not been answered. Lengthy labour and traumatic delivery have previously been shown to affect EAS and PFM strength and their innervation\textsuperscript{15,22,43,45} so an effect on fatigue rate is expected. Again, a larger study, powered to take account of the 21\% Caesarean section rate\textsuperscript{134} is required to answer this question.

- Can maternal pelvis size be measured accurately and safely in pregnancy and does this relate to measured differences in pelvic floor function post partum?

Antero-posterior maternal pelvis size can be measured safely by means of ultrasound pelvimetry in both the pregnant and non-pregnant woman. It is repeatable, but accuracy, compared with MR measurements, is doubted. Accuracy may be improved by measuring women when they have a full bladder, which could form part of future studies. There was no effect of cephalopelvic disproportion on delivery or pelvic floor function post partum, although the study size may have been insufficient to show any differences.

The specific aims of this study have been variably met, adding a little to our understanding of the pathophysiology of FI. However, the ultimate aim is to find a screening tool which could be universally used after childbirth to identify the women at increased risk of developing faecal incontinence. Fatigue rate was felt to be a potential candidate as a screening test, because it measures both muscle and nerve function, is simple, safe and painless to carry out with relatively inexpensive equipment.
However:

"In order to be able to establish a screening programme, it is necessary to fulfil the following criteria.

- There must be a diagnostic test available that can practically be applied to large numbers of people and can be repeated on different occasions in the same individual.
- The test must have high levels of sensitivity (the proportion of tests carried out in individuals who have the disease that detect the disease) and specificity (the proportion of positive tests that are due to the disease, rather than other diseases or artefacts).
- The test must give comparable results between different centres.
- It must be possible to apply the test to a high proportion of the target population
- There must be established and effective treatments for the disease.
- There must be evidence that screening for the disease in question can reduce levels of morbidity and mortality from that disease."

I would argue that fatigue measurement, whether that of EAS or the PFM, has not yet been shown to meet these criteria. Fatigue measurement is highly variable. This variability appears to be intra-individual variability, rather than a systematic error in the repeated measures, evidenced by the low bias. Inter-observer repeatability has not been studied in this thesis, although previous work has shown a good correlation but wide limits of agreement for inter-observer repeatability of EAS fatigue. Although changes in the pelvic floor were found as a result of childbirth, these measured changes have not been definitively linked to alterations in pelvic floor symptoms. In the pilot study, the MSP fell in all 19 primigravid women who delivered vaginally and the FR fell in all bar two of these women. Of the 27 women studied, three developed faecal incontinence post partum and a further 13 reported new flatal incontinence. In the current study, anal resting pressure fell post partum in four cases, squeeze pressure fell in 12 cases, 1st measurement of fatigue was slower post partum in 12, 2nd measurement of fatigue was slower in 10, but in 7 cases the change in fatigue rates differed between the two measurements of fatigue, i.e. if FR1 was slower post partum, than FR2 was not necessarily slower post partum. Six women reported incontinence to flatus (occasional or sometimes) and another two reported faecal incontinence, one to liquid stool rarely and the other to solid stool rarely. However, since the changes measured
post partum in the anal canal by the pilot study, although not confirmed by the current study, and the changes in the pelvic floor musculature are the same as the changes in the anal canal and PFM seen in incontinent subjects, and since pelvic floor disorders are more common in parous women than nulliparous women, it is not illogical to conclude that the injury caused by childbirth and measured by changes in anal and PFM fatigue is the same injury which causes pelvic floor disorders, FI in particular.

**What next?**

Our theory of the pathophysiology of idiopathic faecal incontinence is that childbirth causes damage to the innervation of the pelvic floor musculature, including the innervation of the external anal sphincter. This injury causes a selective loss of type II muscle fibres, resulting in reduced squeeze pressure. Reinnervation causes fibre type grouping and previously type II muscle fibres start synthesising the slow-myosin isoform, becoming type I muscle fibres. This is manifest in a slowing in the fatigue rate. Subsequent events, e.g. the menopause, aging, result in further weakening of the anal sphincters and symptomatic incontinence. (From page 118)

Relating this study back to our overarching theory of the pathophysiology of idiopathic FI, this study has suggested that a reduction of EAS squeeze pressure and fatigue rate occur as a result of childbirth, although results are conflicting. Histological studies are required to determine if the reduced squeeze pressure is subsequent to loss of type II muscle fibres and the alteration in fatigue rate does result from increased proportion of type I fibres. Histological studies are also required to determine if the measured changes in EAS strength and fatigue seen in incontinent subjects are also due to the proposed muscle histochemical changes. Similar studies are required to explore the reasons behind the measured changes in PFM strength and fatigue.

Reduced anal pressure and fatigue rate were almost universal findings in the pilot study. If childbirth is the initial injury, with fatigue reflecting the nature of this injury, further understanding is required to establish why some women develop FI when others do not, since the proposed screening test identifies almost all the study population to have sustained the proposed denervating
injury. It may be that the EAS fatigue rate was not significantly different post partum in the current study because recovery of the pelvic floor and EAS had occurred by the time of measurement, which was greater than that used in the pilot study. We have no knowledge of the fatigue rate in the years after delivery and before the onset of FI, so large, long term studies are required to identify which features of reduced fatigue rate are indicative of increased risk of developing future incontinence.
8. References and Appendices
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Appendix 1: How to make manometry balloons

Equipment

Protect-A-Line 1, non-distendable syringe driver tubing, (code 832.01, Vygon, Cirencester) – cut into 8 lengths
Hospital balloons, latex microballoon (ST3514, Precision Dippings Marketing Ltd, England)
BD Connecta, Luer-Lok 3-way tap with extension (ref 394995, Hecton Dickinson Infusion Therapy AB, Helsingborg, Sweden)
Heatshrink sleeving, (e.g. ELEK0157A, ElecTek, Cambridgeshire, or from B&Q)
Waterproof glue (e.g. Serious glue, Evo-Stik)
Ruler with centimetre marks
Tipex or marker pen

Method

Cut the syringe driver tubing into 8 lengths. Remove the connecters from each end. Trim the latex balloons by about half the length, then slide one onto a piece of syringe driver tubing, till the balloon sits at the end of the tubing. Glue this in place by first rolling the balloon up, applying small dap of glue to tubing, then rolling balloon back down over tubing over top of applied glue. If time allows, leave it to dry over night. Cut length of heat shrink sleeving, sufficient to cover latex and a little more. Slide this up the syringe driver tubing and over the latex to sit at the base of the balloon. A twisting action can be helpful. Use a heat source (e.g. hair dryer) to shrink the sleeving. This creates a water-proof seal and stops pressure from compression of the balloon being dissipated by the balloon coming away from the tubing, rather than force being transmitted down the tubing. Cut the BD Connecta such that around 1 cm of tubing is left attached to the 3-way tap. Feed this onto the opposite end of the syringe driver tubing. Immerse in water and fill the balloon and tubing with water, taking care to remove all air bubbles. Dry and apply 1 cm markings along the tubing from the base of the balloon for 5 cm.
Appendix 2: Calculation of area under the curve of EAS fatigue measurement

Worked example:

The pressure measurements for each time point are presented in an Excel spreadsheet and a graph of pressure against time is generated. Calculation of the area under the curve involves the following steps:

1. Calculation of resting pressure, which falls between the beginning and end of the fatigue measurement in some subjects.
2. Subtraction of resting pressure at each time point from the measured squeeze pressure, to give just the rise above resting pressure for each time point.
3. Addition of all the positive values between the start of the rise in pressure to 20 seconds (600 data points) beyond maximum pressure generated.
Step 1: Calculation of resting pressure
In this example, resting pressure falls from 149 cmH₂O before fatigue reading to 88 afterwards. This is a fall of \( ((149-88)/149) \times 100 = 40.9\% \).

The equation of the line joining these two resting pressures is now calculated using simultaneous equations:

1. \( 149 = 73m + c \)
2. \( 88 = 800m + c \)

Therefore, \( c = 149 - 73m \)

And \( 88 = 800m + 149 - 73m \)

So \( m = (88 - 149)/(800 - 73) = -0.0839 \)

\( c = 149 - 73 \times -0.0839 = 155.13 \)

Step 2: Subtraction of resting pressure from recorded pressure
Put a column of numbers corresponding to the row numbers into column K. In column L, insert the equation of the line of resting pressure, i.e. \( =-0.0839*L1+155.13 \). Copy this into the rest of the column.

Now, in column B, subtract the value in L from the value in A, i.e. cell B1=A1-L1. Copy this into the rest of the column. Then in column C, insert the IF statement (\( =\text{IF}(B1>0,B1,0) \)) to eliminate negative values.

Step 3: Addition of squeeze values
The area under the fatigue curve is calculated by adding the values in column C between the beginning of the fatigue measurement, to 20 seconds (or 600 data points) from the point of maximal pressure, i.e. in this example, from data point 73, where pressure starts to rise to data point 693, which is 600 beyond the point of maximal pressure. This ensures that 20 seconds of squeeze is included in the area calculation. Adding all the values to the point of return to resting pressure would introduce variability between the area calculations, because not all squeezes are exactly 20 seconds long.
Appendix 3: Results of anal manometry and fatigue in primigravid women

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Booking anal fatigue graphs

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ID3


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Third trimester fatigue graphs

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Booking pelvic floor fatigue graphs

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Third trimester pelvic floor fatigue graphs
Post partum pelvic floor fatigue graphs

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