Hip and Pelvic Floor Strength and Mobility in Women with and without Urgency and Frequency Predominant Lower Urinary Tract Symptoms

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Hip and Pelvic Floor Strength and Mobility in Women with and without Urgency and Frequency Predominant Lower Urinary Tract Symptoms

by

Stefanie N Foster

A dissertation presented to
The Graduate School
of Washington University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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List of Abbreviations

2-D = two-dimensional
3-D or 3D = three-dimensional
4-D = four-dimensional (continuously updated three-dimensional ultrasound image)
A = anus
ADF = ankle dorsiflexion
ARA = anorectal angle
AUC = area under the curve (pressure multiplied by time), endurance measure for pelvic floor
B = bladder
BMI = body mass index
CI = confidence interval
cmH$_2$O = centimeters of water (vaginal squeeze pressure)
FADIR = flexion, adduction, internal rotation impingement test
FAIS = femoroacetabular impingement syndrome
HCG = human chorionic gonadotropin
HOOS = Hip Disability and Osteoarthritis Outcome Score
HRGP = hip-related groin pain
ICC = intraclass correlation coefficient
IQR = interquartile range
LPA = levator plate angle
LUTS = lower urinary tract symptoms
N = Newtons
PERFECT = acronym for clinical assessment of pelvic floor muscle function representing
Power, Endurance, Repetitions, Fast contractions, Every Contraction Timed

PFIQ-7 = Pelvic Floor Impact Questionnaire Short Form 7

PFM = pelvic floor muscle

PR = puborectalis (muscle)

PS = pubic symphysis

PVR = post-void residual (urine)

R = rectum

REF = horizontal reference line perpendicular to the ultrasound head

SD = standard deviation

TPUS = transperineal ultrasound

U = urethra

UCLA = University of California Los Angeles (Activity Score)

UF-LUTS = urgency and frequency predominant lower urinary tract symptoms

V = vagina
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Female Pelvic Medicine and Reconstructive Surgery faculty
Movement Science Program peers and friends

It takes a village. Thanks, y’all.

Stefanie N Foster

Washington University in St. Louis
January 2021
Dedicated to my family.
Urgency and frequency are common lower urinary tract symptoms (LUTS) in women and are accompanied by substantial activity and participation restrictions. Medical management begins with ruling out organ pathologies, typically followed by fluid intake and timed voiding often combined with pharmacologic management, and may progress to nerve stimulation, botulinum injections, or surgery where indicated. Despite abundant management options for urgency and frequency predominant LUTS (UF-LUTS) and high financial burden, patients often experience only partial relief from medical treatments for LUTS. While a great deal of literature exists to inform pharmacologic and surgical care of patients with UF-LUTS, less is known about the movement system and its relevance to UF-LUTS. This project sought to inform our understanding of movement system components that may influence either the individual’s experience of the symptoms or associated activity and participation restrictions with the hope that our work may eventually inform nonpharmacologic or nonsurgical treatment. Pelvic floor muscle (PFM) strength and endurance are typical body function intervention targets in patients with UF-LUTS as they may be necessary to engage the voluntary urinary inhibition
reflex. But PFM strength and endurance have not been studied in participants with and without UF-LUTS. Alternatively, some have theorized that PFM strength and endurance may not be the most important targets in patients with UF-LUTS, and suggested that instead, PFM overactivity or impaired mobility may be more important to assess and treat. Clinical observations suggest PFM mobility is impaired in patients with UF-LUTS and this has been theorized to contribute to impaired pelvic circulation and/or reduced degrees of freedom for neural structures innervating the urinary system and related musculoskeletal structures.

Overall, the focus of this project was to understand how body functions of PFM strength, PFM mobility and hip muscle strength differ between women with UF-LUTS and control participants without UF-LUTS, and if these factors are associated with symptoms and the impact of those symptoms on activity and participation. In Chapter 2, we compared hip and PFM strength in women with and without UF-LUTS. We hypothesized that cases with UF-LUTS would have weaker hip external rotator and abductor muscles, similar PFM strength, and poorer PFM endurance than controls without UF-LUTS. Our first hypothesis was supported: our results showed that women with UF-LUTS had weaker hip external rotator and abductor muscles. We did not find differences in PFM strength or endurance between women with and without UF-LUTS. Our study was underpowered to detect case-control differences in PFM strength and endurance, so we cannot say with certainty that no differences exist.

In Chapter 3, we used dynamic transperineal ultrasound imaging to compare PFM position and mobility in women with and without UF-LUTS. We hypothesized that women with UF-LUTS...
would demonstrate elevated resting position of the PFMs and decreased pelvic landmark excursion in relation to pelvic landmarks during contraction and during bearing down as compared to women without UF-LUTS. Our hypothesis was partially supported. Compared to those without UF-LUTS, women with UF-LUTS demonstrated a significantly greater levator plate angle at rest (more cranial and anterior PFM position) and less pelvic landmark excursion (puborectalis muscle lengthening) from rest to bearing down.

This project highlights hip muscle strength and pelvic floor position/mobility as body functions of likely importance in women with UF-LUTS. We discovered that women with UF-LUTS have weaker hip external rotator and abductor muscles, more elevated resting position of the PFMs, and poorer pelvic landmark excursion (PFM lengthening) when cued to bear down than women without UF-LUTS. Clinical assessment of hip muscle strength and PFM position and mobility may better inform nonpharmacological treatment of patients with UF-LUTS. Further work is needed to better understand the mechanisms underlying these relationships and the efficacy of addressing these impairments through intervention.
1. INTRODUCTION

1.1 Prevalence, Burden and Medical Management

Lower urinary tract symptoms (LUTS) include storage (e.g. urgency and frequency), sensory, voiding, and post-micturition symptoms.\textsuperscript{1} Urgency and frequency are the most common LUTS in women.\textsuperscript{2} Urgency is defined as the complaint of a sudden, compelling desire to pass urine which is difficult to defer.\textsuperscript{1} Urinary frequency is a complaint that micturition occurs more frequently during waking hours than previously deemed normal by the woman.\textsuperscript{1} LUTS affect an estimated 75\% of women, however less than a third of women with LUTS seek treatment.\textsuperscript{3} Patients with LUTS experience difficulties with occupational and social activities\textsuperscript{4} and experience embarrassment that can limit their help-seeking behaviors.\textsuperscript{5} Patients with LUTS report poorer quality of life, work productivity, quality of sleep, depression, and anxiety than age-matched controls.\textsuperscript{6-8} The economic burden of LUTS in the US is high with national costs projected over $82 billion by 2020.\textsuperscript{9}

Despite these options and high financial burden, patients often experience only partial relief from medical treatments for LUTS\textsuperscript{10,11} and often self-discontinue medications due to bothersome side effects.\textsuperscript{12} Our project focuses on selected body functions that may influence either the individual’s experience of the symptoms or associated activity and participation restrictions (Figure 1.1), with the hope that our work may eventually inform nonpharmacologic or nonsurgical treatment by targeting the movement system. While strong evidence exists to
support the use of pelvic floor muscle (PFM) training in treating stress urinary incontinence (involuntary leakage on effort or exertion, sneezing or coughing),\textsuperscript{13,14} little is known about effective rehabilitation strategies for patients with urgency and frequency predominant LUTS (UF-LUTS), but without incontinence. Therefore, we chose to focus our studies on participants with UF-LUTS without stress incontinence. Clinically, these individuals might be diagnosed with “overactive bladder” – either “dry” (when no urine leakage occurs), or “wet” (when accompanied by urgency urinary incontinence,\textsuperscript{15} or leakage associated with a sudden, compelling desire to void). Throughout our work, we have chosen to use the label UF-LUTS to describe our participants who were recruited for the presence of urgency and frequency. We acknowledge that UF-LUTS very often overlap with sensory, voiding, and post-micturition LUTS,\textsuperscript{3} and participants with these additional symptoms were not excluded from our analysis. Because we were interested in the movement system functions that may be associated with symptoms of urgency and frequency, we recruited patients reporting these symptoms using specific criteria, outlined in Chapters 2 and 3. The clinical diagnosis of overactive bladder was not required to participate in this study.
1.2 Theorized Modifiable Movement System Functions

While a great deal of literature exists to inform pharmacologic and surgical care of patients with UF-LUTS, less is known about the movement system and its relevance to UF-LUTS. This project sought to inform our understanding of movement system components of UF-LUTS: body functions of PFM strength and endurance (1.2.1), PFM mobility (1.2.2), and hip muscle strength (1.2.3). Section 1.2 outlines existing literature and theories underlying why these body functions are of interest in those with UF-LUTS.
1.2.1 PFM Strength and Endurance

It has been theorized that PFM function is important for patients with UF-LUTS because PFM contraction inhibits bladder muscle (detrusor) contraction through the “voluntary urinary inhibition reflex.” However, PFM strength and endurance have not been studied in participants with and without UF-LUTS, and some have theorized that PFM strength and endurance may not be the most important targets in patients with UF-LUTS (1.2.2). Often inferences about PFM function are made based on the efficacy of PFM training, but these inferences should be approached with caution due to the variability among intervention protocols and study outcomes. While literature reports successful treatment of incontinence with PFM training, literature specific to improvement of urgency and frequency symptoms is limited. In several clinical trials reporting urgency or frequency as an outcome, PFM training alone was unable to produce significant improvements in most participants. Because no tests of PFM strength were conducted as outcomes for these trials, we cannot be certain whether their protocol was ineffective at improving urgency for a large percentage of those participants because it was ineffective at improving PFM strength and endurance, or because strength and endurance are not the appropriate targets for patients with UF-LUTS.
1.2.2 PFM Mobility

Many have theorized that, rather than poor strength and/or endurance, patients with UF-LUTS have PFM overactivity or impaired mobility.\textsuperscript{21–24} Figure 1.2 demonstrates a theoretical continuum of pelvic floor muscle health. Although the real clinical picture for many patients is more complex, this theory helps illustrate why PFM weakness may be important for patients with stress incontinence, represented on the left of the figure, but may not be important patients with UF-LUTS, represented on the right.

\begin{figure}[h]
\centering
\includegraphics[scale=0.8]{figure1.png}
\caption{Theoretical spectrum of pelvic floor health with stress urinary incontinence on the left, and UF-LUTS on the right}
\end{figure}

Clinical observations suggest women with UF-LUTS have excessively elevated PFM position at rest and impaired mobility with PFM contraction and bearing down.\textsuperscript{23} Just like any other healthy muscle, the PFMs must be able to fully contract and relax. The PFMs also must have sufficient mobility to move in parallel motion with the respiratory diaphragm during breathing\textsuperscript{25,26} and allow complete voiding of bladder and bowel. During expiration and voluntary PFM contraction,
the PFMs should move cranially (perineal elevation). 25,27–29 During inspiration and bearing down, the PFMs should move caudally (perineal descent). 25,29

Perpetual motion of the PFMs is theorized to be important for maintaining healthy pelvic circulation by providing a “sump pump” to quicken venous and lymphatic return and allow fresh oxygenated blood access to pelvic organs such as the bladder. 30 Chronically impaired pelvic circulation (ischemia), is associated with LUTS. 31 This ischemia can be detrimental to the sensory processes of the urothelium in the bladder and proximal urethra, which are perfused by a particularly dense capillary network. 32 Ex-vivo 33 and animal 34 studies have demonstrated that, in the case of overactive bladder, hypoxia leads to gene-mediated changes which drive the urothelium to become even more sensitive to mechanical stimuli (such as bladder or urethral stretch). Increased sensitivity in the urothelium may lead to a desire to void prior to the bladder being full, as can occur in UF-LUTS. Therefore, impaired mobility of the PFMs may be associated with UF-LUTS due to impaired circulation.

Another theoretical mechanism linking impaired PFM mobility to LUTS is that when mobility of PFMs are impaired, mechanically stimulated alterations to neural afferent signals occur. For example, PFM mobility impairment may influence urinary afferent signals at the level of 1) the urothelium, and/or 2) peripheral nerves innervating the bladder, urethra and pelvic floor (e.g., branches of the pelvic, hypogastric, and pudendal nerves). The urothelium responds to mechanical stresses including tension, torsion, and movement of visceral organs. 35 The urothelium may produce signals that are interpreted by the brain as bladder filling when the bladder, urethra and associated connective tissues move abnormally within the pelvic cavity. Impaired mobility of the PFMs and/or elevated position of the pelvic floor may reduce the
degrees of freedom in which the bladder, urethra, neural and connective tissues are able to move in response to changes in body position and body movement. Similarly, if impaired PFM position and mobility reduce degrees of freedom for sliding and gliding of peripheral afferent nerves which transmit information about bladder volume to the central nervous, the result can be hyperestheia\textsuperscript{36} of the sensation of the need to urinate. Inflammatory factors induced by the ischemia mentioned above may also contribute to reduced freedom of movement by creating mechanical cross-linking between urinary tract and pelvic floor tissues which would normally be permitted to slide and glide during everyday movement.

1.2.3 Hip Muscle Strength

A third body function often not considered in the treatment of UF-LUTS is hip muscle strength. A small but growing number of studies suggest that hip muscle performance may be associated with PFM performance or symptoms of pelvic floor disorders, including LUTS. The obturator internus, a deep external rotator of the hip, attaches to the PFMs via the arcus tendineus fasciae pelvis (arcus tendineus).\textsuperscript{37} The connection between the obturator internus and the arcus tendinous is important because the PFMs have very small physiological cross-sectional area and may not be able to produce forces associated with normal use on their own without sufficient tension in the arcus tendinous and obturator internus muscle.\textsuperscript{38} Because the hip abductor muscles work in concert with the hip external rotator muscles to stabilize the hip in the transverse plane,\textsuperscript{39} the hip abductor muscles were also of interest. Habitual hip adduction during activities of daily living has been observed among women with urgency,\textsuperscript{40,41} and that habitual hip adduction may be
associated with hip abductor muscle (particularly gluteus medius) weakness. Gluteus maximus, which contributes to hip abduction, also has a morphological and functional connection to the PFM s via connective tissue septa in the ischioanal fossa. Significant weakness in hip external rotator and abductor muscles have been found among patients with stress urinary incontinence compared to asymptomatic participants. However, hip muscle impairments have not been studied in women with UF-LUTS. Figure 1.3 illustrates theorized mechanistic underpinnings of limitations in PFM and hip muscle function and their relationship to UF-LUTS.

Figure 1.3 Model of theoretical mechanistic relationships of interest in this study. Bolded text represents body functions investigated in this study. Bold arrows represent established associations. Thin arrows represent hypothesized relationships. Italicized boxes represent theoretical mechanism underlying symptoms associated with UF-LUTS.
1.3 Focus of the Project

Overall, the focus of this project was to understand how body functions of PFM strength, PFM mobility and hip muscle strength differ between women with UF-LUTS and control participants without UF-LUTS, and if these factors are associated with measures of UF-LUTS symptoms and quality of life (impact of UF-LUTS on activity and participation) (Figure 1.1).

Chapter 2 compares PFM strength, PFM endurance, hip external rotator strength and hip abductor strength between women with and without UF-LUTS in a case-control study. Based on clinical observations and previous literature comparing patients with and without stress urinary incontinence,\textsuperscript{45-47} we hypothesized that cases with UF-LUTS would not have different PFM strength than controls. Based on a theory that women with UF-LUTS may have increased tonic activity of the PFMs as their system attempts to inhibit the detrusor muscle throughout the day, we hypothesized that cases with UF-LUTS would have poorer endurance induced by muscle fatigue compared to controls. Based on clinical observations and previous literature comparing patients with and without stress urinary incontinence,\textsuperscript{44,45} we hypothesized that cases with UF-LUTS would have weaker hip external rotator and abductor muscles compared to controls.

Chapter 3 compares PFM position and mobility between women with and without UF-LUTS in a case-control study. We hypothesized that women with UF-LUTS would demonstrate elevated resting position of the PFMs and decreased excursion of pelvic landmarks during contraction (perineal elevation) and during bearing down (perineal descent), representing impaired mobility as compared to controls.
Appendix A explored whether the above impairments were associated with symptoms and quality of life among those with UF-LUTS. Due to the exploratory nature of this question and small sample size, this information is presented as a brief report in an appendix rather than a full chapter for publication.

Appendix B is a publication reporting on a separate project also completed during the doctoral training period, using baseline data from participants with hip-related groin pain enrolled in a larger clinical trial. It examined whether smaller static ankle dorsiflexion angles were associated with altered ankle, hip and pelvis kinematics during step-down in people with hip-related groin pain.

1.4 Brief Overview of Procedures

We matched cases and controls to mitigate confounding of age,\textsuperscript{7,48} body mass index (BMI)\textsuperscript{7,49} and vaginal parity\textsuperscript{48,50} because these factors are known to influence pelvic floor muscle architecture and urinary symptoms. We measured PFM strength with a vaginal manometer, a one-inch diameter tube that is inserted vaginally and measures PFM squeeze pressure in centimeters of water. Vaginal manometry is one of the oldest and most widely used methods to quantify PFM strength,\textsuperscript{51} and is both reliable and correlated with other methods of determining PFM strength.\textsuperscript{47,52} To compare to previous studies, we used peak vaginal squeeze pressure during a maximum voluntary contraction as our measure of strength, and average pressure over a 10 second maximum voluntary contraction as our measure of endurance.\textsuperscript{53} We used hand dynamometry to measure hip strength due to its clinical applicability. We used isometric make
tests incorporating a strap for resistance to reduce the influence of examiner’s strength on the measures. Transperineal ultrasound imaging has been used to evaluate PFM position and mobility in patients with pelvic organ prolapse, stress urinary incontinence and pelvic pain. Typically, position and/or mobility have been assessed with 3-D and 4-D ultrasound units found in obstetric physician practices. However, we chose to use dynamic 2-D ultrasound imaging because is more affordable and is increasingly popular in pelvic and women’s health specialty physical therapist practices.

1.5 Impact

A great deal of literature on UF-LUTS exists related to mechanisms that inform pharmacologic and surgical care, however the importance of the movement system should not be understated. We know that UF-LUTS are present and bothersome in individuals well under age 65, and our work demonstrates associated impairments in body function are present in younger ages as well. Although little at this time is known about the lifetime course of UF-LUTS progression, it is possible that attention to impairments in body function at earlier time points (e.g., assessment of muscle strength and mobility) may provide a foundation of knowledge to prevent more severe disability in later life in addition to improving symptoms and quality of life. This dissertation presents emerging evidence highlighting the importance of assessing hip muscle strength and PFM mobility in women with UF-LUTS, most of whom were under the age of 45. Although the efficacy of treatment aimed at addressing hip muscle strength and PFM mobility is unknown in patients with UF-LUTS, our findings suggest this may be a future direction of interest.
1.6 References


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Chapter 2:

Hip and Pelvic Floor Muscle Strength in Women with and without Urgency and Frequency Predominant Lower Urinary Tract Symptoms

This work has been accepted for publication and is included with permission of the journal.

2.1 Abstract

**Background:** Urgency and frequency are common lower urinary tract symptoms (UF-LUTS) in women. There is limited evidence to guide physical therapist-led treatment.

**Objectives:** To compare hip and pelvic floor muscle strength between women with and without UF-LUTS. We hypothesized women with UF-LUTS would demonstrate 1) diminished hip external rotator and abductor strength and 2) equivalent pelvic floor strength and diminished endurance compared to controls.

**Study Design:** Case-control study

**Methods:** Women with UF-LUTS (cases) and controls were matched on age, body mass index (BMI), vaginal parity. Examiner measured participants’ 1) hip external rotator and abductor strength via dynamometry (maximum voluntary effort against fixed resistance) and 2) pelvic floor muscle strength (peak squeeze pressure) and endurance (squeeze pressure over a 10 second hold) via vaginal manometry. Values compared between cases and controls with paired-sample t-tests (hip) or Wilcoxon signed rank tests (pelvic floor).

**Results:** 21 pairs (42 women): Hip external rotation (67.0 ± 19.0 N vs 83.6 ± 21.5 N; P=0.005) and hip abduction strength (163.1 ± 48.1 N vs 190.1 ± 53.1 N; P=0.04) were significantly lower in cases than controls. There was no significant difference in pelvic floor strength (36.8 ± 19.9 cmH₂O vs 41.8 ± 21.0 cmH₂O; P=0.40) or endurance (234.0 ± 149.6 cmH₂O*seconds vs 273.4 ± 149.1 cmH₂O*seconds; P=0.24).
**Conclusion:** Women with urgency/frequency had weaker hip external rotator and abductor muscles, but similar pelvic floor strength and endurance compared to controls. Hip strength may be important to assess in patients with UF-LUTS, further research is needed.
2.2 INTRODUCTION

Urgency and frequency are common lower urinary tract symptoms (LUTS) in women² and substantially interfere with daily activities.³,⁴ Medical management begins with ruling out organ pathologies, typically followed by fluid intake and timed voiding often combined with pharmacologic management, and may progress to nerve stimulation, botulinum injections, or surgery where indicated.⁵,⁶ Despite abundant management options for urgency and frequency predominant LUTS (UF-LUTS) and high financial burden,⁷ patients often experience only partial relief from medical treatments for LUTS.⁸⁻¹⁰ To develop better treatment options for patients with UF-LUTS, we must first understand factors that may be associated with UF-LUTS.

Pelvic floor muscle (PFM) training is a common nonpharmacological management strategy with strong evidence to support its use in those with stress incontinence.¹¹ One theory behind using PFM training in women with UF-LUTS is that PFM contraction inhibits detrusor contraction through the “voluntary urinary inhibition reflex.”¹² However, researchers who have studied PFM training typically use reduction of urinary incontinence as the primary outcome and rarely report outcomes associated with urgency and frequency.¹³ Therefore women with UF-LUTS but without incontinence may not benefit from PFM training in the same way. Another assumption behind using PFM training as a treatment is that PFM strength and/or endurance are impaired in patients with UF-LUTS, however this assumption has not been investigated. Further, a small treatment trial demonstrated that 43% of patient with UF-LUTS did not have resolution of urgency after 12 weeks of standard PFM training.⁹ Many have suggested that PFM training may not be effective for those with UF-LUTS because their PFM are overactive rather than weak.¹⁴⁻¹⁷ We theorized that Increased tonic activity of the PFMs as their system attempts to inhibit the detrusor muscle or prevent urine loss throughout the day, may lead poorer endurance induced by
muscle fatigue. To test the assumption that PFM training is beneficial for women with UF-LUTS, we must first understand whether UF-LUTS is associated with PFM weakness or poor endurance.

One factor often not considered in treatment of UF-LUTS is hip muscle strength. A small but growing number of studies suggests that hip muscle performance may be pertinent to PFMs and pelvic floor disorders, including LUTS.\textsuperscript{18–21} The obturator internus, a deep external rotator of the hip, attaches to the PFMs via the arcus tendineus fasciae pelvis (arcus tendineus). The connection between the obturator internus and the arcus tendinous is important because the PFMs have very small physiological cross-sectional area and have been theorized to require sufficient tension in the arcus tendinous and obturator internus muscle to produce forces associated with normal use.\textsuperscript{22} Because the hip abductor muscles work in concert with the hip external rotator muscles to stabilize the hip in the transverse plane,\textsuperscript{23} the hip abductor muscles were also of interest. Habitual hip adduction during activities of daily living has been observed among women with urgency,\textsuperscript{18} and may be associated with hip abductor muscle (particularly gluteus medius) weakness.\textsuperscript{24} Significant weakness in hip external rotators\textsuperscript{20} and abductors\textsuperscript{20,21} has been found among patients with stress urinary incontinence compared to asymptomatic participants; however, the relationship between hip muscle performance and UF-LUTS has not been studied.

The objective of this study was to compare hip and pelvic floor muscle strength between women with and without UF-LUTS via hip muscle force dynamometry and PFM manometry. We hypothesized that 1) women with UF-LUTS would demonstrate decreased hip external rotator and abductor strength as compared to women without UF-LUTS, and 2) women with UF-LUTS would demonstrate comparable PFM strength and diminished endurance as compared to women without UF-LUTS.
2.3 MATERIALS AND METHODS

2.3.1 Study Design

The study was a 1:1 matched case-control study of women with and without UF-LUTS. The study was approved by the Human Research Protection Office of Washington University in St Louis (approval #201810086) and conducted in accordance with the Declaration of Helsinki. Participants gave written informed consent prior to participation.

2.3.2 Participants

From April to December 2019, female participants 18-60 years of age were recruited from the community via paper and social media advertisements, emails, and research recruitment fairs. Participants with UF-LUTS (“cases”) were included if they experienced bothersome urinary urgency (sudden need to rush to urinate) and/or frequency (more frequent than every 2 hours)\(^{25}\) on a typical day in the past 4 weeks, as reported during a phone screen. Because the current International Continence Society (ICS) definition of frequency is not specific, “complaint that voiding occurs more frequently than deemed normal by the individual,”\(^{26}\) we used more frequent than every 2 hours as an additional criteria to ensure discrimination between cases and controls. Women without UF-LUTS (“controls”) were matched 1:1 to cases based on age ± 5 years, body mass index (BMI) ± 5 kg/m\(^2\) and vaginal parity (0, 1, >1). Women with stress or mixed incontinence were excluded. Women with urgency urinary incontinence\(^{27}\) were included. Full inclusion and exclusion criteria are listed in Table 2.1.
### TABLE 2.1
Inclusion and exclusion criteria for all participants with and without urgency and frequency predominant lower urinary tract symptoms (UF-LUTS)

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria (n=42)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All</strong></td>
<td></td>
</tr>
<tr>
<td>• Women, ages 18-60</td>
<td>• Stress urinary incontinence or mixed incontinence more than once per month</td>
</tr>
<tr>
<td>• Able to speak and understand English</td>
<td>• Current or recurrent urinary tract infection or gynecologic infection or cancer</td>
</tr>
<tr>
<td></td>
<td>• Symptomatic pelvic organ prolapse</td>
</tr>
<tr>
<td></td>
<td>• Previous surgery for prolapse or incontinence</td>
</tr>
<tr>
<td><strong>Cases w/ UF-LUTS (n=21)</strong></td>
<td></td>
</tr>
<tr>
<td>• Bothersome urgency or frequency in the past 4 weeks</td>
<td>• Hip, pelvic, or trunk trauma or cancer</td>
</tr>
<tr>
<td></td>
<td>• Abdominal or pelvic surgery in the past year</td>
</tr>
<tr>
<td></td>
<td>• Current injury that would limit their ability to participate in testing</td>
</tr>
<tr>
<td></td>
<td>• Onabotulinumtoxin injections to the bladder, pelvic floor or hip muscles</td>
</tr>
<tr>
<td></td>
<td>• Vulvovaginal dermatological conditions associated with UF-LUTS</td>
</tr>
<tr>
<td><strong>Controls (n=21)</strong></td>
<td></td>
</tr>
<tr>
<td>• No UF-LUTS in the past 6 months</td>
<td>• Diabetes</td>
</tr>
<tr>
<td>• Age, BMI, &amp; parity matched to cases</td>
<td>• Current pregnancy or birth/termination/miscarriage in the past 12 weeks</td>
</tr>
<tr>
<td></td>
<td>• Neurological involvement that would influence their coordination or balance</td>
</tr>
<tr>
<td></td>
<td>• Implanted devices that impair the ability to visualize / make ultrasound measures</td>
</tr>
</tbody>
</table>

---

**2.3.3 UF-LUTS and Activity Assessment**

Study data were collected and managed using REDCap electronic data capture tools. Prior to examination, participants completed questionnaires including the LUTS Tool for a comprehensive assessment of participants’ LUTS, the Pelvic Floor Impact Questionnaire short form (PFIQ-7) for a general overview of impact of symptoms on daily activities and quality of life, and the UCLA Activity Score for a general overview of activity and exercise level.
2.3.4 Final Eligibility Exam

A single assessor, a physical therapist trained in intravaginal pelvic floor examination, completed all measurements. To determine final eligibility, urine and pelvic organ prolapse screens were completed. Using 10SG and human chorionic gonadotropin (HCG) test strips (McKesson, Irving, TX, USA), participants were excluded if their urine tested positive for glucose, nitrite, blood, leukocyte esterase, or HCG. After urine screening, a transabdominal ultrasound scan confirmed whether the bladder was empty. If postvoid residual urine was evident, participants were asked to void again prior to intravaginal exam. A screening exam for symptomatic prolapse was performed with the participant supine with knees bent and feet flat on the exam table. A lubricated sterile wide tongue depressor was used to retract the vaginal wall as the participant bore down. Participants were excluded if any intravaginal landmark descended beyond the vaginal introitus (hymenal ring) because prolapse at or beyond this point has been associated with symptomatic prolapse.32,33

2.3.5 Hip Muscle Strength

A microFET3 hand-held dynamometer (Hogan Health Industries, Salt Lake City, UT, USA) was used to assess hip muscle strength. Isometric make tests34 were used, incorporating a strap for fixed resistance to minimize the effect of assessor strength on measurements. Isometric make tests with a hand dynamometer and strap have been found to be valid for measuring hip strength compared to isokinetic dynamometry.35 Hip external rotation force was measured in sitting with the hip at 90 degrees of flexion and neutral hip rotation (Figure 2.1). Hip abduction was measured in side-lying with pillows supporting the test hip at neutral abduction, rotation and
flexion/extension (Figure 2.2). Participants completed one submaximal practice trial and three maximal 3 second measurement trials for each muscle group on each hip. The three trials for each hip were averaged for analysis. To estimate the size of the difference between readings, 10 participants completed a second testing session, within two weeks of the first testing session. The average between-reading difference for external rotation was 1.7 Newtons (N) (95% CI: 0.4 to 3.8) and for abduction was 7.7 N (95% CI: 8.5 to 23.9).

Figure 2.2 Hip External Rotator Isometric Make Test

With hip flexed to 90 degrees, participants externally rotated their hip as strongly as possible against fixed resistance of the strap. Peak force in Newtons was measured by a handheld dynamometer inside the strap. Peak force in Newtons was measured by a handheld dynamometer inside the strap at 4cm proximal to the medial malleolus.
2.3.6 Pelvic Floor Muscle Strength and Endurance

Prior to vaginal squeeze pressure measurement, the examiner palpated vaginally while participants were cued to “squeeze and lift the PFMs as if you’re stopping your urine stream or trying to hold back gas.” If participants were unable to perform the movement appropriately, brief verbal instruction with confirmatory palpation was given in an effort to obtain valid squeeze pressure measurements. Vaginal manometry is commonly used as a “gold standard” and considered to be a valid measure of PFM strength when accompanied by an inward lift of the perineum.\textsuperscript{36}
Vaginal squeeze pressure was measured using a Peritron Perineometer and single-participant-use vaginal pressure sensors (Laborie, Williston, VT, USA). Participants were examined in supine with knees bent, feet flat on the exam table, and hips in neutral internal/external rotation. The sensor was lubricated and inserted vaginally until 1 cm of the blue sheath remained external. If, due to pain, the participant was unable to tolerate sensor insertion, vaginal manometry was not completed. After insertion and a 60 second acclimation period, the manometer was zeroed. For each strength trial, participants were instructed to squeeze and lift the PFMs as strongly as possible, hold for 10 seconds while the assessor counted audibly with a clock, then relax completely. Participants performed a brief submaximal practice trial with no hold followed by 3 trials in which peak pressure, duration of contraction, and average pressure over the trial were recorded by the manometer. The participants were given 30 seconds rest between trials. For each of the 3 trials, area under the curve (AUC) metric was computed by multiplying duration by average pressure of the trial. Peak pressure and AUC were averaged across the 3 trials for each participant. PFM strength was assessed via peak vaginal squeeze pressure in cmH$_2$O, and PFM endurance was assessed using the AUC metric over the 10 second hold in cmH$_2$O*sec. To estimate the size of the difference between readings, 9 participants completed a second testing session, within two weeks of the first testing session. The average between-reading difference for peak was 2.2 cmH$_2$O (95% CI: 0.0 to 10.3) and for AUC was 57.0 cmH$_2$O*seconds (95% CI: 10.6 to 103).
2.3.7 Sample Size

Because no data had been published on the primary study measures in patients with UF-LUTS by the start of the study, we computed interim effect sizes for hip external rotation and abduction force using means and standard deviations of the differences between the first 10 complete case-control pairs and G*Power (Heinrich-Heine-Universität Düsseldorf, DE). We powered the study on hip strength variables because we were most interested in hip strength as a novel variable in patients with UF-LUTS. Cohen’s $d$ effect sizes were computed for hip abduction force as 0.84 and for hip external rotation as 0.56. With Cohen’s $d$ having a minimum of 0 (no effect) and a theoretical maximum value of 1.00, these effect sizes can be interpreted as large and medium, respectively. These effect sizes were similar to another study measuring hip external rotation in similarly aged healthy women ($d = 0.78$). Based on these estimates, we determined we needed a total sample size of 44 participants (22 matched case-control pairs) to detect differences in hip external rotation strength with 80% power, an alpha level of 0.05, and a paired sample two-tailed $t$-test.

2.3.8 Statistical Analysis

Statistical analyses were computed using SAS (SAS Institute Inc., Cary, NC, USA). Descriptive statistics were computed for participant characteristics and questionnaire scores. Because case-control pairs were 1:1 matched, paired-samples tests were used to compare participant characteristics, hip external rotator and abductor force, vaginal squeeze pressure peak and endurance, UCLA activity, LUTS Tool scores, and PFIQ-7 scores between cases and matched
controls. One-tailed tests were used for hip strength and pelvic floor endurance outcomes due to a priori directional hypotheses. Assumptions were checked graphically with histograms and Q-Q plots and statistically with the Shapiro Wilk test. When the between-pair difference was not normally distributed, Wilcoxon’s signed rank test was used as a nonparametric alternative.

2.4 RESULTS

A total of 21 case-control pairs (42 women) were enrolled with adherence to 1:1 matching rules. We were unable to enroll 22 total pairs during our predetermined study timeline. No participants were excluded based on the prolapse screening exam. Mean age of our sample was 28.5 years and all but one pair were nulliparous. There were minimal, nonsignificant, differences between cases and controls by age, BMI and vaginal parity (Table 2.2). Women with UF-LUTS had significantly worse LUTS Tool Storage and Voiding Symptom and Bother scores and significantly worse PFIQ-7 Urogenital Impact scores (Table 2.2). Median LUTS Tool Scores for those with UF-LUTS represented mild to moderate symptoms and bother. None of our sample had ever used medications for LUTS. Complete data for 21 pairs were available for hip external rotator and abductor strength. For PFM strength and endurance, data for 17 pairs were available because 4 participants (3 cases, 1 control) were unable to tolerate insertion of the vaginal manometer due to pain.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>UF-LUTS (n=21)</th>
<th>Control (n=21)</th>
<th>Summary statistics (UF-LUTS minus Control)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years, mean ± SD [range])</td>
<td>28 ± 10 [19-56]</td>
<td>29 ± 9 [21-57]</td>
<td>-0.9 ± 3 [-5 - 4]</td>
<td>0.12</td>
</tr>
<tr>
<td>BMI (kg/m², mean ± SD [range])</td>
<td>24 ± 4 [18-35]</td>
<td>25 ± 4 [19-33]</td>
<td>-0.4 ± 2 [-4 - 4]</td>
<td>0.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Vaginal parity (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>95</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Race (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>19</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black or African American</td>
<td>5</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>76</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other or Mixed-race</td>
<td>0</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethnicity (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hispanic or Latino</td>
<td>14</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Hispanic or Latino</td>
<td>86</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCLA Activity Score (Median [IQR])</td>
<td>9 [5]</td>
<td>6 [5]</td>
<td>0.3 [3.6]</td>
<td>0.64</td>
</tr>
<tr>
<td>LUTS Tool (Median [IQR])</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUTS Storage Bother</td>
<td>8 [4]</td>
<td>0 [0]</td>
<td>8 [5]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LUTS Voiding Bother</td>
<td>2 [3]</td>
<td>0 [0]</td>
<td>2 [3]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Pelvic Floor Impact Questionnaire - 7 (median [IQR])</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFIQ-7 Urogenital</td>
<td>24 [24]</td>
<td>0 [0]</td>
<td>24 [24]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>PFIQ-7 Colorectal</td>
<td>0 [5]</td>
<td>0 [0]</td>
<td>0 [5]</td>
<td>0.004</td>
</tr>
<tr>
<td>PFIQ-7 Vagina/Pelvis</td>
<td>0 [5]</td>
<td>0 [0]</td>
<td>0 [5]</td>
<td>0.02</td>
</tr>
</tbody>
</table>

LUTS=Lower Urinary Tract Symptoms; SD=standard deviation; IQR=interquartile range defined as the 75th minus the 25th percentile.

<sup>a</sup>P value from two-tailed paired samples t-test (all others from two-tailed Wilcoxon signed rank)

The UCLA Activity Score is an ordinal self-report scale from 1 (No activity) to 10 (Regularly participates in high impact activity).

LUTS Tool scores were obtained by summing the frequency of LUTS (0-5) within each respective domain. The number of component items summed for each scale is: Storage Symptom 5, Storage Bother 4, Voiding Symptom 8, Voiding bother 7.
2.4.1 Hip Muscle Strength

A bilateral mean was used for analysis. A sensitivity analysis was performed where strength from a single hip was selected at random. The conclusions were unchanged. Participants with UF-LUTS had significantly less hip external rotation strength (67.0 ± 19.0 N vs 83.6 ± 21.5 N; \(P=0.005\)) and hip abductor strength (163.1 ± 48.1 N vs 190.1 ± 53.1 N; \(P=.04\)) compared to control participants (Figures 2.3 and 2.4).

*Significantly greater in Control compared to UF-LUTS, per one-tailed paired t-test; \(X\) represents mean, line represents 50th percentile, error bars represent minimum and maximum

Figure 2.3 Hip External Rotator Strength in women with and without urgency and frequency predominant lower urinary tract symptoms (UF-LUTS)

Figure 2.4 Hip Abductor Strength in women with and without urgency and frequency predominant lower urinary tract symptoms (UF-LUTS)
2.4.2 Pelvic Floor Muscle Strength

No significant differences were observed between women with UF-LUTS and matched controls in PFM strength (36.8 ± 19.9 cmH₂O vs 41.8 ± 21.0 cmH₂O; \( P=0.40 \)) or endurance (234.0 ± 149.6 cmH₂O*seconds vs 273.4 ± 149.1 cmH₂O*seconds; \( P=0.24 \)) (Figures 2.5 and 2.6).

![Figure 2.5 Pelvic Floor Muscle Strength - Peak Vaginal Squeeze Pressure (cmH2O) in women with and without urgency and frequency predominant lower urinary tract symptoms (UF-LUTS)](image1)

![Figure 2.6 Pelvic Floor Muscle Endurance - Vaginal Squeeze Pressure over 10 second hold (cmH2O*seconds) in women with and without urgency and frequency predominant lower urinary tract symptoms](image2)

\( \dagger \)No significant paired differences, per two-tailed Wilcoxon signed ranks test; X represents mean, line represents 50\(^{th}\) percentile, error bars represent minimum and maximum

\( \dagger \)No significant paired differences, per one-tailed Wilcoxon signed ranks test; X represents mean, line represents 50\(^{th}\) percentile, error bars represent minimum and maximum
2.5 DISCUSSION

2.5.1 Principal Findings

Our study observed that women with UF-LUTS had less hip external rotator and abductor strength, but similar PFM strength and endurance compared to women without UF-LUTS. We report novel information about the role of hip muscle and PFM strength in women with UF-LUTS without stress incontinence. Our results suggest that assessing hip muscle performance may be important for those with UF-LUTS. Intervention studies for this treatment strategy have not yet been conducted. Further research is required to better understand the role of PFM performance in UF-LUTS.

2.5.2 Research Implications

We found weakness in hip external rotators and abductors in women with UF-LUTS. Our results are consistent with studies of women with stress urinary incontinence that found women with stress urinary incontinence had less hip abductor strength\textsuperscript{20,21} than controls; previous studies that compared hip external rotator strength in women with and without stress incontinence have reported mixed results.\textsuperscript{20,21} Future research to better understand the relationship of hip muscle strength and symptoms should investigate whether strengthening hip external rotators and abductors can improve UF-LUTS. Previous studies have found hip strengthening can improve symptoms of stress incontinence\textsuperscript{39} and other pelvic floor dysfunction.\textsuperscript{40} The fact that hip strength differed between women with and without UF-LUTS, but PFM strength and endurance did not, suggests the influence of hip strength on UF-LUTS is not purely via an effect on PFMs.
Investigation into potential musculoskeletal underpinnings of UF-LUTS from the hip and pelvis are warranted. Hip muscle weakness may be related to habitual hip adduction motion or posturing that has been associated with UF-LUTS, but the causal pathway is not yet understood. Gluteus maximus, which contributes to hip abduction, also has a morphological and functional connection to the PFMs via connective tissue septa in the ischioanal fossa. Future studies would benefit from measuring global hip muscle function, including hip extension.

We did not find PFM weakness in women with UF-LUTS as measured by peak volitional vaginal squeeze pressure and a ten second hold. Our results are consistent with studies that found women with stress urinary incontinence did not have worse PFM strength than women without. This may indicate force production capability alone may not be the most important factor among patients with UF-LUTS. Perhaps different parameters of PFM performance are more important to UF-LUTS such as PFM mobility and coordination in response to daily activity demands. Mobility of the PFMs (ability to move through full range of motion for contraction and relaxation) may be important as evidenced by known associations between difficulty relaxing PFMs and LUTS such as urgency, frequency, hesitancy, dysuria and pain. However, PFM mobility has yet to be studied systematically in patients with UF-LUTS. PFM function in response to demands of activities of daily living and exercise may be more important than a voluntary response to verbal cuing. UF-LUTS respond to qualitative changes in common daily movements, and thus, the response of PFMs to movement and activities of daily living may be important to capture in future studies.
2.5.3 Clinical Implications

Given that women with UF-LUTS demonstrated hip muscle weakness compared to asymptomatic controls, a more thorough musculoskeletal assessment may be warranted, including assessment of hip muscle strength. Based on our findings and previous literature, patients with LUTS with or without incontinence may benefit from hip strengthening. Previous work has demonstrated improved pelvic floor muscle strength\textsuperscript{19,40} and decreased pelvic floor dysfunction\textsuperscript{39,40} after a hip strengthening program. Further research is required to assess the efficacy of hip strengthening in improving UF-LUTS. As this type of intervention poses minimal risk, a hip strengthening protocol under physical therapist supervision may be warranted on a trial basis for patients with UF-LUTS.

Our results suggest PFM weakness may not be a primary factor in UF-LUTS and other factors may need to be considered. Stress incontinence literature suggests PFM training results in patient-reported symptom improvement.\textsuperscript{11} Interestingly, studies comparing PFM strength between those with and without incontinence report no differences in baseline PFM strength, similar to our findings.\textsuperscript{20,21,42} PFM training may be targeting mechanisms additional to PFM force production. Among PFM training programs is a wide variety in emphasis on improving parameters of PFM performance including strength, endurance, power, muscle tone, coordination, motor control, flexibility, and myofascial pain. This varying emphasis may explain why intervention studies have shown positive effects of PFM training while case-control studies have not shown differences in PFM strength and endurance. There may also be a subset of individuals who benefit from particular PFM-focused interventions. Because PFM performance parameters other than strength and endurance may contribute to UF-LUTS, we recommend assessment of PFM and surrounding muscle coordination during activities meaningful to the
and systematic palpation of each PFM for myofascial pain or symptom reproduction\textsuperscript{46} to determine an individualized approach.

\textbf{2.5.4 Strengths and Limitations}

A major strength of this study is the inclusion of control participants matched one to one to cases on age, BMI and vaginal parity which helped to focus the study on the relationship of muscle performance to UF-LUTS and reduce confounding factors. Systematic procedures for examination were tested for reliability, and a single examiner performed all testing. The similarity of our findings in women with UF-LUTS without stress incontinence and previous studies of women with stress incontinence lends support to our observation that in symptomatic women compared to controls, hip external rotators\textsuperscript{20} and hip abductors\textsuperscript{20,21} are weaker, but PFM strength\textsuperscript{20,21,42} and endurance are no different.\textsuperscript{20}

Our sample size for PFM measures was reduced because 4 women (3 UF-LUTS and 1 control) were unable to tolerate the vaginal manometer probe. These 4 women were not statistical outliers on any other variables tested, and variable means and dispersions looked similar whether PFM measures were analyzed pairwise with 17 pairs, or unpaired with 38 total participants. Our study was not powered to detect differences in PFM strength or endurance, but the within-pair differences we found in PFM strength are likely not clinically important. Effect sizes for PFM strength (peak squeeze pressure in cmH\textsubscript{2}O) and endurance (cmH\textsubscript{2}O*seconds) were small, and a much larger sample size would be needed to achieve 80% power at alpha=.05 (n=177 for peak cmH\textsubscript{2}O and n=134 for cmH\textsubscript{2}O*seconds). Peak vaginal squeeze pressures measured for women with UF-LUTS in our study (mean 36.9 cmH\textsubscript{2}O, 95% CI: 27.3, 46.5) were comparable to those in
healthy asymptomatic women of similar age in previous studies (summary mean 38.1 cmH₂O, 95% CI: 34.6, 41.5).19,44,47,48 It was not possible to blind the single examiner to participant symptom status, but systematic examination procedures and equipment were in place to minimize bias. Our sample skewed toward participants between age 18 and 35 (only 3 pairs were over age 35) and mostly nulliparous. Our participants tended to report low to moderate UF-LUTS severity, likely due to being recruited from the general population rather than a population of women seeking treatment. Because we were interested in clinical tests that could be completed by physical therapists and under budgetary constraints, we do not have urodynamic data on participants in our sample. General activity levels, as reported in the UCLA Activity Score, were similar between cases and controls. Given our small sample size, we limited our analyses to those we had determined a priori and did not assess the relationship between activity level and our variables of interest. We do not know how our results may have differed in a population age over 35, parous, less physically active, and more severely symptomatic. Although our sample may not be reflective of most clinical populations, UF-LUTS are present in women under age 454,49,50 and our data points to the presence of bothersome symptoms prior to seeking medical attention and a willingness of these women to participate in research. Our hope is that continued inclusion of women in studies who have not yet sought medical attention for UF-LUTS will improve early education and treatment efforts in the future.

2.6 Conclusions
Our study found women with UF-LUTS have weaker hip external rotators and abductors than women without UF-LUTS, but similar PFM strength and endurance. Further research is needed to determine whether strengthening hip external rotators and abductors can improve UF-LUTS.
2.7 REFERENCES


doi:10.1097/JWH.0000000000000086


40. Tuttle LJ, Autry T, Kemp C, et al. Hip exercises improve intravaginal squeeze pressure in
doi:10.1080/09593985.2019.1571142


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The authors would like to thank Darrah Snozek for her assistance with screening and data collection.
Chapter 3:

Pelvic Floor Mobility measured by Transperineal Ultrasound Imaging in

Women with and without Urinary Urgency and Frequency

This work has been submitted for publication and is currently under review.

3.1 ABSTRACT

Aims

To compare pelvic floor muscle (PFM) position and mobility measured by 2-D dynamic transperineal ultrasound (TPUS) at rest, with a maximal PFM contraction (perineal elevation), and with bearing down (perineal descent) in women with and without urgency- and frequency-predominant lower urinary tract symptoms (UF-LUTS). We hypothesized that women with UF-LUTS would demonstrate elevated resting position and decreased excursion of pelvic landmarks during contraction and bearing down as compared to women without UF-LUTS.

Methods

This was a case-control study of women with and without UF-LUTS, without incontinence, matched 1:1 on age, body mass index and vaginal parity. TPUS videos were obtained during 3 conditions: rest, with PFM contraction, and with bearing down. Anorectal angle (ARA), Levator plate angle (LPA) and distance from pubis to rectum (PR length) were measured offline for each condition. Paired t-tests or Wilcoxon signed rank tests compared LPA and PR length between cases and controls.

Results

21 case-control pairs (42 women) completed testing. Women with UF-LUTS compared to controls demonstrated greater LPA at rest (66.8 ± 13.2 degrees vs 54.9 ± 9.8 degrees; P=0.006), and less PR lengthening from rest to bearing down (0.2 ± 3.1 mm vs 2.1 ± 2.9 mm; P=.03).
Conclusions

Women with UF-LUTS demonstrated more elevated (cranial anterior) position of the PFM at rest and less PR muscle lengthening with bearing down. These findings highlight the importance of a comprehensive PFM examination and treatment for women with UF-LUTS to include PFM position and mobility.
3.2 INTRODUCTION

Urinary urgency and frequency are the most common lower urinary tract symptoms (LUTS) in women and present a substantial burden on patients’ activities and quality of life. Behavioral therapies targeting the pelvic floor muscles are commonly prescribed for patients with LUTS. Pelvic floor muscle (PFM) training is the most frequently cited therapy and is highly effective for patients with stress urinary incontinence but may not be effective for urgency and frequency predominant LUTS (UF-LUTS) without incontinence. We have demonstrated that a marker of PFM strength (vaginal squeeze pressure) does not differ between women with and without UF-LUTS, suggesting other parameters of PFM performance should be considered.

PFM mobility may be one such parameter of interest. Clinical observations suggest women with UF-LUTS have excessively elevated PFM position at rest and limited mobility with PFM contraction and bearing down. Just like any other healthy muscle, the PFM must be able to move through the full range of motion: fully contract and relax. The PFM must also have sufficient mobility to move in parallel motion with the respiratory diaphragm during breathing and sufficient relaxation to allow for complete voiding of bladder and bowel. Clinical assessment of PFM function includes assessment of mobility and quality of motion during PFM contraction, relaxation, and bearing down. In women, this assessment is often completed by the practitioner palpating vaginally to determine the resting position of the PFM, and the direction and quantity of motion during contraction and bearing down. However, PFM vaginal palpation is not always feasible or ideal for a variety of reasons: not all patients are comfortable with vaginal palpation; practitioner’s palpating digit may provide tactile feedback that causes the patient’s PFM to perform differently than they might otherwise; and vaginal palpation does not allow for measurement of PFM mobility. Ultrasound imaging of pelvic landmark excursions
during contraction (perineal elevation) and bearing down (perineal descent) may provide a noninvasive quantitative method to assess PFM mobility.\textsuperscript{13}

Two-dimensional (2-D) dynamic ultrasound is inexpensive and increasingly available in physician and physiotherapist offices. Transperineal ultrasound (TPUS) has long been used for biofeedback in training the PFMs to voluntarily contract, primarily in patients with urinary incontinence.\textsuperscript{14} Transperineal ultrasound measurement during voluntary PFM contraction is reliable and associated with both PFM manual muscle testing and vaginal squeeze pressure measurements.\textsuperscript{15} However, research is lacking in the use of TPUS to examine resting position and mobility of the PFMs in patients with conditions where PFM mobility is suspected to be reduced, such as UF-LUTS.

The objective of our study was to compare PFM position and mobility in women with and without UF-LUTS via 2-D dynamic TPUS imaging at rest, with a maximal PFM contraction, and with bearing down. We hypothesized that women with UF-LUTS would demonstrate elevated resting position and decreased muscle excursion in relation to pelvic landmarks during contraction and during bearing down as compared to women without UF-LUTS.

3.3 MATERIALS AND METHODS

3.3.1 Participants

Participants were recruited as part of a 1:1 matched case-control study to examine hip and pelvic floor muscle strength differences in women with and without UF-LUTS.\textsuperscript{7} The study was approved by the Human Research Protection Office of Washington University in St Louis and
conducted in accordance with the Declaration of Helsinki. Participants gave written informed consent prior to participation. From April to December 2019, female participants 18-60 years of age were recruited from the community via paper and social media advertisements, emails, and research recruitment fairs. Participants with UF-LUTS (“cases”) were included if they experienced bothersome urinary urgency (sudden need to rush to urinate) and/or frequency (0-2 hours between needing to empty your bladder), during a typical day in the past 4 weeks as reported during a phone screen. Women without UF-LUTS (“controls”) were matched 1:1 to cases based on age ± 5 years, body mass index (BMI) ± 5 kg/m² and vaginal parity (0, 1, >1). These matching criteria were selected to eliminate potential confounding influences on pelvic floor muscle. Potential participants were excluded if they reported stress urinary incontinence more than once per month; current or recurrent urinary tract or gynecologic infection or cancer; previous surgery for prolapse or incontinence; hip, pelvic, or trunk trauma or cancer; abdominal or pelvic surgery in the past year; or implanted devices in the pelvis that impair the ability to visualize structures of interest on ultrasound. Detailed exclusion criteria are listed in TABLE 3.1.
### TABLE 3.1 Inclusion and exclusion criteria for study participants

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All:</strong></td>
</tr>
<tr>
<td>• Women ages 18-60 able to speak and understand English</td>
</tr>
<tr>
<td><strong>Urgency and Frequency Lower Urinary Tract Symptoms (UF-LUTS):</strong></td>
</tr>
<tr>
<td>• Bothersome urgency or frequency in the past 4 weeks</td>
</tr>
<tr>
<td><strong>Controls:</strong></td>
</tr>
<tr>
<td>• No UF-LUTS in the past 6 months</td>
</tr>
<tr>
<td>• Age, BMI, &amp; vaginal parity matched to cases</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Stress urinary incontinence or mixed incontinence more than once per month</td>
</tr>
<tr>
<td>• Current or recurrent urinary tract infection(^a) or gynecologic infection or cancer</td>
</tr>
<tr>
<td>• Symptomatic pelvic organ prolapse(^a)</td>
</tr>
<tr>
<td>• Previous surgery for prolapse or incontinence</td>
</tr>
<tr>
<td>• Hip, pelvic, or trunk trauma or cancer</td>
</tr>
<tr>
<td>• Abdominal or pelvic surgery in the past year</td>
</tr>
<tr>
<td>• Current injury that would limit their ability to participate in testing</td>
</tr>
<tr>
<td>• Onabotulinumtoxin injections to the bladder, pelvic floor or hip muscles</td>
</tr>
<tr>
<td>• Vulvovaginal dermatological conditions associated with UF-LUTS</td>
</tr>
<tr>
<td>• Diabetes</td>
</tr>
<tr>
<td>• Current pregnancy(^a) or birth/termination/miscarriage in the past 12 weeks</td>
</tr>
<tr>
<td>• Neurological involvement that would influence their coordination or balance</td>
</tr>
<tr>
<td>• Implanted devices that impair the ability to visualize / make ultrasound measures</td>
</tr>
</tbody>
</table>

\(^a\)Items ruled out during final eligibility exam

#### 3.3.2 Self-Report Questionnaires

Study data were collected and managed using REDCap electronic data capture tools.\(^{16}\) Prior to examination, participants completed questionnaires including the LUTS Tool\(^{17}\) for a comprehensive assessment of participants’ LUTS, and the Pelvic Floor Impact Questionnaire short form (PFIQ-7)\(^{18}\) for a general overview of impact of symptoms on daily activities and quality of life.
3.3.3 Final Eligibility Exam

A single assessor, a physiotherapist trained in vaginal pelvic floor examination, completed all exams. To determine final eligibility, a urine screen for current urinary tract infection and pregnancy and a pelvic organ prolapse screen were completed. After urine screening, a transabdominal ultrasound scan confirmed whether the bladder was empty. If postvoid residual urine was evident, participants were asked to void again until the bladder was empty as viewed on the scan prior to vaginal exam.

3.3.4 Transperineal Ultrasound Acquisition Procedure

Transperineal ultrasound (TPUS) images were acquired by a physiotherapist trained in pelvic floor imaging using a Clarius C3 curvilinear scanner (Clarius Mobile Health Corp, Burnaby BC) with a disposable cover with conducting gel applied above and below the cover. With participants positioned supine with knees bent and feet flat on the exam table, the probe was placed on the perineum in a midsagittal plane oriented cranially. The image acquisition angle was set at the device maximum 73 degrees in the midsagittal plane and the image was optimized to visualize from pubis to the deepest region of interest, the anorectal angle. Participants were instructed in the motion sequence and cued during each trial to “relax 1, 2, 3, squeeze and lift the PFMs as if you’re stopping your urine stream or trying to hold back gas, relax 1, 2, 3, then bear down as if you’re trying to have a bowel movement.” A practice trial was performed and imaged to ensure the participant understood the instructions and that all regions of interest remained in frame throughout the sequence. Three study trials of the entire sequence were video recorded with no identifying annotations. Videos were stored on a secure server. Prior to image
measurement, ultrasound video files were given a random code and the key was inaccessible to the blinded study assessor.

3.3.5 Transperineal Ultrasound Measurement Methods

Measurements were developed by two experts in pelvic health physiotherapy (TS and SF), adapted from 4-D ultrasound methods. Measurement protocol specified to watch each saved ultrasound video to select three static frames: at rest, peak contraction, and peak bearing down. For each frame, Fiji image analysis platform was used to measure the anorectal angle (ARA), the levator plate angle (LPA), and the puborectalis muscle length (PR length) (FIGURE 1). The ARA was defined as the angle between the rectal ampulla and the anal canal using the posterior edge of the hypoechojenic lumen as a guide. The LPA was determined by one line from the posterior-inferior pubis to the vertex of the ARA and another from the pubis horizontally across the image (perpendicular to the transducer). Motion of clitoral and connective tissue was used to distinguish the stationary border of the posterior/inferior pubis. Anorectal angle excursion values were computed by subtracting the ARA at rest from the ARA at contraction or bearing down. A decreasing ARA (negative excursion) represented closing the ARA (more acute), while an increasing ARA (positive excursion) represented widening the ARA (more obtuse). Levator plate angle excursion values were computed by subtracting the LPA at rest from the LPA with contraction or bearing down. An increase in the LPA (positive excursion) represented PFM motion in the cranial and anterior direction, while a decrease in the LPA (negative excursion) represented motion in a caudal and posterior direction. Bearing down results in PFM motion in the caudal and posterior direction, thus decreasing LPA. The PR length was recorded as a 2-D
representation of the length of the puborectalis muscle. Coordinates in millimeters were recorded for the vertices of the ARA and LPA and the PR length was defined as the distance in millimeters from the LPA vertex on the pubis to the ARA vertex. PR length change was computed by subtracting the length at rest from the length at contraction or bearing down. A decrease in the PR length (negative excursion) represented PFM shortening, while an increase in PR length (positive excursion) represented muscle lengthening. For each measure, the mean of 3 participant trials was used for analysis.

Figure 3.1 Transperineal Ultrasound Midsagittal View and Measurements.

PS, pubic symphysis; U, urethra; V, vagina; REF, horizontal reference line perpendicular to sound head; LPA, levator plate angle; B, bladder; PR, puborectalis length; A, anus; R, rectum

3.3.6 Rater Reliability and Measurement Selection

A research assistant, trained in the standardized procedures, was blinded to participant symptom status and other exam data throughout the study and completed all official study measures. Prior to obtaining official study measures, a training period served to ensure that the research assistant and trainer agreed on their measurements. During this training period and subsequent protocol refinement, it was discovered that the anorectal angle was difficult to measure reliably due to indistinct margins of the posterior anus and rectum. Though interrater ICCs improved after training and refinement (post-training ICCs reported in TABLE 3.2), the anorectal angle
remained a difficult measurement to make reliably and a decision was made to not include the
ARA in further analysis. In advance of future studies, we were also interested to know how much
between-session variability existed in participant performance for these measures. To compute
test-retest reliability for LPA and PR length, we repeated the ultrasound data collection on 10
participants during a second session scheduled 1-2 weeks after their first appointment. The
research assistant completed blinded image measurements from recorded videos for both
sessions for computation of test-retest reliability (reported in TABLE 3.2).

**TABLE 3.2** Reliability of Dynamic Transperineal Ultrasound Measurements
from Saved Videos

<table>
<thead>
<tr>
<th>Transperineal Ultrasound Measure</th>
<th>Interrater ICC</th>
<th>Test-Retest ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARA at rest / baseline</td>
<td>0.671</td>
<td>N/A</td>
</tr>
<tr>
<td>ARA excursion rest to contract</td>
<td>0.466</td>
<td>N/A</td>
</tr>
<tr>
<td>ARA excursion rest to bear down</td>
<td>0.534</td>
<td>N/A</td>
</tr>
<tr>
<td>LPA at rest / baseline</td>
<td>0.805</td>
<td>0.748</td>
</tr>
<tr>
<td>LPA excursion rest to contract</td>
<td>0.795</td>
<td>0.725</td>
</tr>
<tr>
<td>LPA excursion rest to bear down</td>
<td>0.831</td>
<td>0.563</td>
</tr>
<tr>
<td>PR length at rest / baseline</td>
<td>0.804</td>
<td>0.831</td>
</tr>
<tr>
<td>PR length excursion rest to contract</td>
<td>0.932</td>
<td>0.803</td>
</tr>
<tr>
<td>PR length excursion rest to bear down</td>
<td>0.692</td>
<td>0.831</td>
</tr>
</tbody>
</table>

ARA, Anorectal angle; LPA, Levator Plate Angle; PR, Puborectalis; Interrater ICC, two-way
random effects absolute agreement; Test-Retest ICC, two-way mixed effects absolute agreement
measured between two participant testing sessions.

### 3.3.7 Statistical Analysis

Sample size was determined for the primary study that was designed to detect differences in hip
external rotator strength between women with and without UF-LUTS. Statistical analyses were
computed using SAS software, version 9.4 of the SAS System for Windows (SAS Institute Inc.,
Cary, NC, USA). Descriptive statistics were computed for participant characteristics and
questionnaire scores. Case and control participants were matched 1:1 on key variables, therefore
paired-samples two-tailed t-tests were used to compare ARA, LPA and PR length at rest,
excursion to contract, and excursion to bulge. Assumptions were checked graphically with
histograms and Q-Q plots and statistically with the Shapiro Wilk test. Where t-test assumptions were violated, Wilcoxon signed-rank tests are reported.

3.4 RESULTS

A total of 21 case-control pairs (42 women) completed testing (TABLE 3.3). Median LUTS Tool Scores for those with LUTS represented mild to moderate symptoms and bother. None of our sample had ever used medications for LUTS. Test-retest reliability ICCs were moderate to good for LPA (0.563 to 0.748) and good for PR length (.803 to .831).
TABLE 3.3  Participant characteristics in women with and without urgency and frequency predominant lower urinary tract symptoms (UF-LUTS)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>UF-LUTS (n=21)</th>
<th>Control (n=21)</th>
<th>Paired Differences</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years, mean ± SD [range])</td>
<td>28 ± 10 [19-56]</td>
<td>29 ± 9 [21-57]</td>
<td>-0.9 ± 3 [-5 - 4]</td>
<td>0.12a</td>
</tr>
<tr>
<td>BMI (kg/m2, mean ± SD [range])</td>
<td>24 ± 4 [18-35]</td>
<td>25 ± 4 [19-33]</td>
<td>-0.4 ± 2 [-4 - 4]</td>
<td>0.40a</td>
</tr>
<tr>
<td>Vaginal parity (%)</td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>0</td>
<td>95</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUTS Tool (Median [IQR])</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUTS Storage Bother</td>
<td>8 [4]</td>
<td>0 [0]</td>
<td>8 [5]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LUTS Voiding Bother</td>
<td>2 [3]</td>
<td>0 [0]</td>
<td>2 [3]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Pelvic Floor Impact Questionnaire - 7 (median [IQR])</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFIQ-7 Urogenital</td>
<td>24 [24]</td>
<td>0 [0]</td>
<td>24 [24]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>PFIQ-7 Colorectal</td>
<td>0 [5]</td>
<td>0 [0]</td>
<td>0 [5]</td>
<td>0.004</td>
</tr>
<tr>
<td>PFIQ-7 Vagina/Pelvis</td>
<td>0 [5]</td>
<td>0 [0]</td>
<td>0 [5]</td>
<td>0.02</td>
</tr>
<tr>
<td>UCLA Activity Score (Median [IQR])</td>
<td>9 [5]</td>
<td>6 [5]</td>
<td>0.3 [3.6]</td>
<td>0.64</td>
</tr>
</tbody>
</table>

LUTS=Lower Urinary Tract Symptoms; SD=standard deviation; IQR=interquartile range defined as the 75th minus the 25th percentile.

aP value from two-tailed paired samples t-test (all others from two-tailed Wilcoxon signed rank test)

The UCLA Activity Score is an ordinal self-report scale from 1 (No activity) to 10 (Regularly participates in high impact activity)

LUTS Tool scores were obtained by summing the frequency of LUTS (0-5) within each respective domain. The number of component items summed for each scale is: Storage Symptom 5, Storage Bother 4, Voiding Symptom 8, Voiding bother 7.
TABLE 3.4 Differences between women with and without UF-LUTS in transperineal ultrasound

<table>
<thead>
<tr>
<th>Transperineal Ultrasound Measure</th>
<th>UF-LUTS</th>
<th>Control</th>
<th>Paired Differences</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPA at rest / baseline</td>
<td>66.8 ± 13.2</td>
<td>54.9 ± 9.8</td>
<td>11.9 ± 17.8</td>
<td>0.006</td>
</tr>
<tr>
<td>LPA excursion rest to contract</td>
<td>10.6 ± 9.2</td>
<td>14.8 ± 5.6</td>
<td>-4.1 ± 11.2</td>
<td>0.10</td>
</tr>
<tr>
<td>LPA excursion rest to bear down*</td>
<td>-4.0 ± 7.8</td>
<td>-6.8 ± 8.4</td>
<td>-0.5 ± 10.5</td>
<td>0.49a</td>
</tr>
<tr>
<td>PR length at rest / baseline</td>
<td>40.6 ± 6.2</td>
<td>43.2 ± 6.4</td>
<td>-2.6 ± 8.7</td>
<td>0.19</td>
</tr>
<tr>
<td>PR length excursion rest to contract</td>
<td>-2.7 ± 3.1</td>
<td>-4.4 ± 3.9</td>
<td>1.7 ± 4.6</td>
<td>0.11</td>
</tr>
<tr>
<td>PR length excursion rest to bear down*</td>
<td>0.2 ± 3.1</td>
<td>2.1 ± 2.9</td>
<td>-2.7 ± 4.7</td>
<td>0.02a</td>
</tr>
</tbody>
</table>

LPA, Levator plate angle; PR, Puborectalis

*Paired differences (UF-LUTS minus Control) are expressed as median ± interquartile range and P values from two-tailed paired Wilcoxon Signed Ranks test, all other paired differences expressed as mean ± standard deviation with P values from paired t-tests

3.4.1 Transperineal Ultrasound Measurement Results

Compared to those without UF-LUTS, women with UF-LUTS demonstrated significantly greater LPA at rest (66.8 ± 13.2 degrees vs 54.9 ± 9.8 degrees; P=0.006) (TABLE 3.4). Those with UF-LUTS also had less PR lengthening from rest to bear down (0.2 ± 3.1 mm vs 2.1 ± 2.9 mm; P=0.03).

3.5 DISCUSSION

We sought to compare PFM position and mobility in women with and without UF-LUTS.

Women with UF-LUTS have relatively elevated PFMs at rest and less lengthening to bear down
compared to women without UF-LUTS, consistent with our stated hypothesis. We did not find differences in excursion from rest to contract for any variable between women with and without UF-LUTS. These findings, together with our findings that PFM strength is similar between women with and without UF-LUTS,\(^7\) suggest that PFM strengthening alone may not result in improvement of UF-LUTS. These results further highlight the importance of a comprehensive PFM examination for women with UF-LUTS including assessment of PFM position and mobility. Further studies are needed to understand the underlying mechanistic connection between the observed PFM position and mobility impairments and UF-LUTS. Future research is also warranted to assess how interventions to optimize PFM position and mobility might improve UF-LUTS and quality of life.

We were unable to find studies that measured PFM position and mobility in patients with UF-LUTS, however studies have assessed PFM position and mobility in participants with pelvic pain. Similar to our findings, Morin et al describe elevated PFM position and poorer PFM mobility in participants with pelvic pain compared to those without.\(^{19}\) Authors compared unmatched women with and without provoked vestibulodynia and reported larger LPA and shorter PR length at rest, and smaller LPA excursion from rest to contraction in women with vestibulodynia. Previous studies have demonstrated an association between myofascial pelvic pain and LUTS,\(^{23,24}\) particularly in younger patients.\(^{24}\) One can postulate that this association may be due in part to similar impaired PFM position and mobility in individuals suffering with pelvic pain or UF-LUTS conditions.\(^8\)
Our findings suggest that PFM position and mobility may be important components of PFM function to consider in the assessment of patients with UF-LUTS. Dynamic TPUS allows for measurements not captured by PFM manometry, electromyography and manual palpation for pain. Existing clinical manual assessment methods of PFM function such as the PERFECT scheme do not measure mobility. Unlike manual assessment, TPUS does not require invasive vaginal or rectal palpation and allows for quantitative measurements. Transperineal ultrasonography provides more detailed muscle visualization compared to transabdominal ultrasound of bladder base elevation and allows visualization of anterior-posterior PFM motion or muscle length change. Future studies are needed to determine how to maximize TPUS capability in the assessment of patients with UF-LUTS.

Using our methods, measurements of LPA and PR length made from saved videos demonstrated reasonable test-retest reliability estimates. We recommend caution in interpreting these measures over multiple sessions in a cohort study or trial due to notable systematic bias observed in some variables from session 1 to session 2 (Supplemental Figure 3.2): LPA excursion to contract tended to decrease, LPA excursion to bear down tended to increase, and PR length tended to decrease. We hypothesize test-retest differences may be due to early motor learning despite no feedback, changes in cuing, or intervention between sessions. Future studies comparing measures of LPA and PR length between dynamic 2-D and 3-D/4-D TPUS would aid in validating the use of 2-D when 3-D/4-D is not available or financially feasible. Given the poor interrater reliability estimates we computed for the ARA, we cannot recommend the ARA be used in future studies with our study device. However, we were able to reliably select the X and Y coordinates of the ARA vertex, allowing for acceptable agreement of LPA and PR length. We believe our transducer’s 73 degree maximum acquisition angle, in many participants, precluded our ability to
maintain the pubis in view while obtaining clear images of the posterior wall of the anal canal without an acoustic shadow. A transducer with a larger acquisition angle might have allowed improved measurement agreement. We would also recommend equipment that allows simultaneous viewing of the entire pubis cross-section and ARA so that the measurement axis could be standardized by a line bisecting the length of the pubic symphysis. We were also limited by the number of participants willing to return for a second testing session and included both cases and controls in our test-retest estimates. Future studies would benefit from comparing test-retest agreement both in symptomatic and asymptomatic participants separately to determine whether one group is more consistent or reliable in their performance of these cued tasks.

A disadvantage specific to the use of 2-D TPUS in our study is that we cannot be certain we captured the absolute minimum hiatal dimensions. We were also unable to view the entire levator hiatus at once and measure or document any defects in the levator ani muscle. However, levator ani defects are likely more pertinent to patients with prolapse and incontinence than patients with UF-LUTS without incontinence. Finally, our participant sample was young and mostly nulliparous so our results may not be generalizable to other clinical populations. However, we sought to clearly assess the differences between women with and without UF-LUTS without the confounding effect of continence before broadening this inquiry to a larger and more clinically complex sample.

Future studies are needed to further investigate assessment using TPUS to inform possible treatment directed at PFM position and mobility in those with UF-LUTS. One potential therapeutic use of TPUS in UF-LUTS is as biofeedback to assist patients in learning to fully relax and coordinate their PFMs during physiotherapist led treatment sessions. Currently, transabdominal ultrasound is often used as biofeedback to teach PFM contraction, but the
transabdominal bladder view of bladder base elevation does not allow measurement nor reference to specific landmarks such as the pubic symphysis. With larger studies to obtain normative data, clinicians can also take measurements with TPUS to compare to normative values and aid in monitoring patient progress with treatment.

3.6 CONCLUSION

We found that women with UF-LUTS compared to women without demonstrated more cranial anterior position of the PFM and less PR muscle lengthening with a cue to bear down. Dynamic 2-D TPUS may be an appropriate noninvasive assessment method yielding novel information in patients with UF-LUTS, potentially functioning as biofeedback and/or a clinical measurement tool, but further studies are needed.

3.7 Funding and Acknowledgements

Funding for the study was provided by The Foundation for Barnes-Jewish Hospital, NIH T32HD007434 and UL1TR002345, Washington University in St. Louis Program in Physical Therapy. The funding sources had no role in study design; in the collection, analysis and interpretation of data; in the writing of the report; or in the decision to submit the article for publication.

The authors would like to thank Darrah Snozek for her assistance with screening and data collection.
Figure 3.2 Supplemental Figure: Test-retest scatterplots for ten participants’ TPUS LPA and PR length measures

Ten participants returned for a second testing session with no intervention to assess test-retest reliability of the measures.
3.8 REFERENCES


doi:10.1007/s10350-004-6155-7


doi:10.1007/s00192-007-0408-7
Chapter 4: Summary

4.1 Main Results

The overall focus of this project was to understand how PFM strength, PFM mobility and hip muscle strength differ between women with UF-LUTS and control participants without UF-LUTS, and if these factors are associated with measures of UF-LUTS symptoms and quality of life. The purpose of this chapter is to summarize the findings of the project, limitations and opportunities for future work.

4.1.1 Chapter 2

In Chapter 2, we compared hip and PFM strength in women with and without UF-LUTS. We hypothesized that cases with UF-LUTS would have weaker hip external rotator and abductor muscles, similar PFM strength, and poorer PFM endurance than controls without UF-LUTS. Our first hypothesis was supported: our results showed that women with UF-LUTS had weaker hip external rotator and abductor muscles. The fact that our cases with UF-LUTS had 20% less hip external rotator muscle strength than controls indicates this external rotator muscle strength is likely a variable of continued interest in research and clinical care for patients with UF-LUTS. This represents an even greater difference than shown in prior work comparing hip external rotator muscle strength between asymptomatic participants and those with stress urinary incontinence (14%)\(^1\) or with hip pain (16%).\(^2\) We found a 14% difference in hip abductor muscle strength between patients with UF-LUTS and controls, and those differences were greater than test-retest differences. Previous literature has shown slightly greater differences in hip abductor
muscle strength between asymptomatic participants and those with stress urinary incontinence (27%)\textsuperscript{1} or with hip pain (22%).\textsuperscript{2,3} Presence or history of hip joint pain most likely did not influence our hip strength results, as 17 cases and 17 controls reported never having had hip joint pain. Only 3 cases and 1 control reported chronic hip joint pain, and 1 case and 3 controls reported any history of hip joint pain.

We did not find differences in PFM strength or endurance between women with and without UF-LUTS. Our study was underpowered to detect case-control differences in PFM strength\textsuperscript{i} and endurance,\textsuperscript{ii} so we cannot say with certainty that no differences exist. However, our results are consistent with studies that found women with stress urinary incontinence did not have worse PFM strength than women without.\textsuperscript{1,4,5} Peak vaginal squeeze pressures measured for women with UF-LUTS in our study (mean 36.9 cmH\textsubscript{2}O, 95% CI: 27.3, 46.5) are similar to those in healthy asymptomatic women of similar age in previous studies (summary mean 38.1 cmH\textsubscript{2}O, 95% CI: 34.6, 42.1).\textsuperscript{6–9} Our results point to the likelihood that PFM variables other than maximum voluntary squeeze pressure or a 10 second hold may be more important to consider in the study and care of those with UF-LUTS. Thus, we explored additional PFM variables in Chapter 3.

\textsuperscript{1} PFM strength (peak vaginal squeeze pressure): Cohen’s d=.217; Post hoc power 13% for n=17, matched Wilcoxon signed ranks test, two-tailed at .05 alpha; 177 pairs needed to achieve 80% power
\textsuperscript{ii} PFM endurance (vaginal squeeze pressure*time over 10 second hold): Cohen’s d=.221; Post hoc power 21% for n=17, matched Wilcoxon signed ranks test, one-tailed at .05 alpha; 134 pairs needed to achieve 80% power
4.1.2 Chapter 3

In Chapter 3, we used dynamic transperineal ultrasound imaging to compare PFM position and mobility in women with and without UF-LUTS. We hypothesized that women with UF-LUTS would demonstrate elevated resting position of the PFMs and decreased pelvic landmark excursion in relation to pelvic landmarks during contraction and during bearing down as compared to women without UF-LUTS. Our hypothesis was partially supported. Compared to those without UF-LUTS, women with UF-LUTS demonstrated a significantly greater levator plate angle at rest (more cranial and anterior PFM position) and less pelvic landmark excursion (puborectalis muscle lengthening) from rest to bearing down. Although not statistically significant in our sample, the mean paired differences for excursion from rest to contraction for both the levator plate angle and puborectalis length were in hypothesized directions: women with UF-LUTS trended toward decreased cranial/anterior excursion in LPA and decreased puborectalis muscle shortening and a larger sampleiii may yield significant results. With our measurements, we are unable to distinguish whether elevated PFM resting position and impaired mobility in those with UF-LUTS are due to muscle shortness, impairments in motor control, or both. However, this provides preliminary work to corroborate clinical observations of impaired position and mobility and highlight the importance of assessing these in patients. Clinical observations suggest that treatment to normalize PFM position and mobility improves symptoms and quality of life in patients with UF-LUTS. Further work is needed to understand the

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iii LPA excursion from rest to contract: Cohen’s d=0.375; post hoc power 37% for n=21 paired t test, two-tailed at .05 alpha; 58 pairs needed to achieve 80% power
PR length excursion from rest to contract: Cohen’s d=0.372; post hoc power 37% for n=21 paired t test, two-tailed at .05 alpha; 59 pairs needed to achieve 80% power
mechanisms underlying this relationship and to prospectively test intervention strategies for patients with UF-LUTS aimed at improving PFM position and mobility.

4.2 Limitations

Limitations are reported in their respective chapter publications, but several are expanded here for discussion.

4.2.1 Unblinded examiner

For this study, it was not possible for the person performing all participant physical exams (myself) to be blinded to participant’s status as case or control. The measures reported in this dissertation were carefully controlled with strict procedures and protocols, cuing scripts, and measurement equipment. Besides feasibility in cost and scheduling personnel, we felt this was a reasonable compromise for our early-stage work, given that I would benefit from a thorough understanding of what was going on with all aspects of the study and to ensure participants were not in distress during testing. Two portions of the examination protocol (not reported in this dissertation) in which participants reported sensations and symptoms would likely have unblinded the examiner: the pelvic floor muscle palpation exam, and the movement system impairment exam. Future study protocols wishing to maintain a blinded examiner will need adequate hours from a research administrator for screening and enrollment, matching and scheduling; a third party unblinded expert in pelvic health as a sounding board for recruitment
and enrollment questions, and protocols in place for participants to report sensations and symptoms directly to an unblinded research assistant without the examiner’s knowledge.

### 4.2.2 Controlled data acquisition is both a strength and a limitation

Experimental controls to mitigate errors, bias and confounding in experiments is vital to the scientific process for validity, reliability and our ultimate trust in the results. Given the early-stage nature of our work, we opted to err on the side of extensive experimental controls in both participant selection criteria and data acquisition conditions. However, these controls do limit the generalizability of our work.

#### 4.2.2.1 Participant selection criteria

Given the abundance of literature on patients with stress urinary incontinence, and that the gold standard treatments that work for patients with stress incontinence aren’t necessarily effective in those without incontinence, we opted to study a subset of patients with LUTS without stress incontinence. Due to stress incontinence and pelvic organ prolapse being on the opposite side of the theoretical continuum of pelvic floor muscle function (Figure 1.1) from UF-LUTS, we also opted to exclude those with prolapse. However in practice, UF-LUTS very often overlap with varying degrees of stress or mixed incontinence, other types of LUTS (such as voiding and post-micturition), prolapse and pelvic pain\(^{11-14}\). Although zero interested participants failed the final eligibility exam due to prolapse, 112 were ineligible at screening based on self-reported stress incontinence (plus or minus additional exclusions). These restrictions resulted in a sample that
was skewed toward younger ages and we only enrolled one pair with any vaginal delivery history. Therefore, these results are not generalizable to typical clinical populations in most female pelvic medicine or women’s and pelvic health specialist physical therapy practices. Patients who experience pelvic floor dysfunction on both ends of the continuum (e.g., urinary frequency and stress urinary incontinence) may require different clinical management strategies than patients with either isolated condition. Additionally, although voiding symptoms (e.g. weak or split urine stream) are more common than storage symptoms in males, UF-LUTS occur in males as well as females. We opted to focus our study on females only because of their high prevalence of storage symptoms and male/female differences in anatomy, pelvic morphometry and measurement equipment. In clinical practice, a highly individualized approach is still required for assessment and treatment of both male and female patients with UF-LUTS with or without comorbidities.

4.2.2.2 Data acquisition conditions

In an effort to optimize reliability of our exam and measurements, all measurements were obtained in standardized static body positions. However, none of these positions (supine hooklying for PFM, and seated or sidelying for hip muscles) mimic the conditions under which these muscles are required to coordinate performance in everyday life. Contraction of the bladder muscle (detrusor) are known to be increased in seated or standing vs supine, but we do not know if changes in detrusor activity correspond to changes in hip or PFM performance. Additionally, we assessed participants’ voluntary response to a cue as is a common way to assess muscle performance in clinical examination and research. However, real life motor control of
both the PFMs and hip muscles is rarely conscious. How these muscles perform in “real world” conditions - upright weight-bearing positions, during functional body movement, and with additional challenges to neuromotor control such as balance perturbations or multiple demands on attention - is of great interest for future work.

4.3 Future Directions

This being early-stage work, there are a myriad of directions that future studies could go. Having worked in a variety of clinical physical therapy settings, I believe understanding common mechanisms is of great interest to inform the most efficient and effective treatment strategies. Hence, my project carved out a tiny piece to inform our understanding of movement system components of UF-LUTS: body functions of hip muscle strength and PFM strength and mobility. As physical therapists globally are increasingly the first healthcare access point for patients with pelvic floor disorders and musculoskeletal pain conditions, our profession’s ability to effectively screen patients for appropriate referral becomes increasingly important in addition to honing our movement system diagnostic skills. A thorough understanding of the interplay between organ pathologies and movement system impairments can inform both screening for referral and movement system diagnoses. Below I introduce three potential future directions of interest in patients with UF-LUTS: additional hip muscles to investigate, real-time changes in symptoms and their relationship to the movement system, and the use of urodynamic testing to link underlying medical diagnoses to movement system diagnoses.
4.3.1 Additional hip muscles of interest

Additional muscles considered to be accessories or synergists with the PFMs (e.g., abdominals, gluteus maximus, and adductors) were not directly assessed in our study and may be of interest for future studies in patients with UF-LUTS. It is well established that abdominal muscles and PFMs co-activate during voluntary PFM contraction and some abdominal exercises in healthy individuals.\textsuperscript{17–19} Gluteus maximus co-activation with PFMs has also been demonstrated in healthy women,\textsuperscript{20,21} likely due to a mechanical connection via the ischiorectal fossa.\textsuperscript{21} Although we did not measure its performance directly, gluteus maximus may have contributed to our hip abduction force measurements,\textsuperscript{22} and hip extension strength may be of interest in future studies. One study has demonstrated co-activation between the PFMs and hip adductors.\textsuperscript{20} PFM contraction alone seems to produce more vaginal squeeze pressure than other accessory isolated muscle contractions,\textsuperscript{23} but, optimal quantity and timing of these accessory muscles’ activation in relation to PFMs is poorly understood and their relevance in patients with UF-LUTS is yet unknown.

4.3.2 Real-time changes due to episodic and situational nature of UF-LUTS

Women with UF-LUTS experience variation in their symptoms based on situation, environment, bladder filling, and body position. For example, common triggers such as unlocking or opening their home’s front or garage door and running water can result in sudden and severe urgency sensation or even urgency incontinence.\textsuperscript{24} Women also report worsening UF-LUTS just before and during menstruation\textsuperscript{25} and with cold weather.\textsuperscript{26} Based on our current work, we cannot say whether the strength, endurance or mobility of hip and pelvic floor muscles varies in real time.
along with the episodic nature of UF-LUTS, and if they do, whether we captured our participants at their best or at their worst. Future investigators would be wise to take potential within-participant symptom and muscle performance variances into account. In those with intact nervous systems, electromyography readings from the urethral sphincter muscle increase involuntarily in real time with bladder filling in a phenomena known as the “guarding reflex.” However, we do not know if real-time changes in urge sensation correspond with any changes in peak pelvic floor muscle squeeze pressure as we measured it. Women report immediate changes in urgency sensation with variations in body position and movement. And, women with and without stress incontinence demonstrate changes in gait mechanics between having no desire to void versus an hour after drinking 16 ounces of fluid. Future work could investigate whether urgency sensation changes in real-time correspond to changes in hip muscle or PFM performance. This question is made challenging by varying rates of urine production and bladder filling throughout the testing session. Controlling participant fluid/food intake for a certain length of time prior to testing may help, but even better may be to monitor bladder volume throughout the session. Monitoring bladder volume is possible with ultrasound imaging and/or urodynamics (4.3.3).

### 4.3.3 Medical diagnoses underlying UF-LUTS and their relationship to movement

Because participants in our study were primarily recruited via flyers and research volunteer registry emails, they had not been medically diagnosed. A myriad of medical diagnoses may have contributed to their self-reported UF-LUTS including conditions of the bladder, urethra,
and nervous system. Incorporation of urodynamics could help determine whether patients with various underlying diagnoses perform similarly in their hip and pelvic floor muscles.

Urodynamic testing is a common component of the diagnostic milieu for patients with UF-LUTS to “identify all factors contributing to lower urinary tract dysfunction and/or are the origin of symptoms and assess their relative importance.” Urodynamic testing provides information about the urethra, detrusor (bladder muscle), bladder sensation, bladder volume capacity, bladder compliance (change in volume divided by change in pressure) and bladder outlet obstruction (obstructed voiding of urine). The site of bladder outlet obstruction can be ascertained by video urodynamics. In females, proposed sites of obstruction include the bladder neck, urethral sphincter, pelvic floor muscle, urethral stricture, and pelvic organ prolapse. For example, it is possible that a person with UF-LUTS may have normal urethral function; normal detrusor (bladder muscle) activity; normal bladder sensation, capacity and compliance; but functional bladder outlet obstruction caused by poor relaxation of the PFM. Although UF-LUTS are often thought to be associated with detrusor overactivity (involuntary contractions of the detrusor during bladder filing), a person may experience increased frequency due to an underactive detrusor muscle and incomplete voiding. For future studies in patients with UF-LUTS, I recommend assessment via noninvasive urodynamics of uroflowmetry and ultrasound measurement of post-void residual (PVR) and bladder wall thickness. If uroflowmetry shows participants to have a maximum urine flow rate less than 15 milliliters per second, a more invasive urodynamic workup may be indicated to rule out bladder outlet obstruction. Post void residual urine indicates the bladder is not fully emptying, and puts individuals at risk for urinary tract infection. Increased bladder wall thickness may indicate a further workup for decreased bladder capacity or bladder outlet obstruction, and suggests a decreased likelihood of bladder
hypersensitivity as a sole underlying cause of UF-LUTS. Whether or not physical therapists should tailor their treatment according to these various combinations of underlying organ conditions is yet unknown. Better understanding relationships between these underlying organ states and movement system function is paramount.

4.4 Conclusion

Our understanding of the movement system in patients with UF-LUTS is wide open for exploration, but this dissertation highlights hip muscle strength and pelvic floor position/mobility as body functions of likely importance. We discovered that women with UF-LUTS have weaker hip external rotator and abductor muscles, more elevated resting position of the PFMs, and poorer pelvic landmark excursion (PFM lengthening) when cued to bear down than women without UF-LUTS. Clinical assessment of hip muscle strength and PFM position and mobility may better inform nonpharmacological treatment of patients with UF-LUTS. Further work is needed to better understand the mechanisms underlying these relationships and the efficacy of addressing these impairments through intervention.


4.5 References


10. Erbes NA, Foster SN, Harris-Hayes M, Spitznagle TM. Movement Impairments in
Women with and without Urinary Urgency/Frequency. Submitted.


Appendix A:

Associations between musculoskeletal impairments and lower urinary tract symptoms, bother and quality of life: A Brief Report
A.1 ABSTRACT

OBJECTIVE: To investigate whether musculoskeletal impairments were associated with severity of urgency and frequency-predominant lower urinary tract symptoms (UFLUTS) and impact on their quality of life. We hypothesized that decreased hip strength, decreased PFM mobility, and elevated PFM position at rest would be associated with worse symptoms (LUTS Tool storage subscale) and quality of life (PFIQ urogenital subscale).

DESIGN: Cross-sectional subanalysis with symptomatic participants in a case-control study

SETTING: Laboratory setting, academic research center

PARTICIPANTS: Women ages 18-60 with bothersome urinary urgency and/or frequency

RESULTS: None of the musculoskeletal variables examined were associated with storage LUTS or quality of life.

CONCLUSIONS: We found no associations between selected musculoskeletal variables and storage LUTS and their impact on quality of life among women with UF-LUTS. However, this analysis was underpowered. A larger study with greater range in participants’ severity of symptoms, bother and impact on quality of life may be more informative.
A.2 INTRODUCTION

In our previous work, we found that women with urgency and frequency predominant lower urinary tract symptoms (UF-LUTS) demonstrated decreased hip strength, decreased pelvic floor muscle (PFM) mobility, and elevated PFM position at rest compared to women without UF-LUTS.1,2 These women with UF-LUTS reported mild to moderate symptoms, bother and impact on their quality of life. We were interested to know whether these musculoskeletal impairments were associated with severity of UF-LUTS symptoms, bother and impact on their quality of life. We hypothesized that decreased hip strength, decreased PFM mobility, and elevated PFM position at rest would be associated with worse symptoms (LUTS Tool storage subscale) and quality of life (PFIQ urogenital subscale).

A.3 METHODS

A.3.1 Participants

Participants for this cross-sectional sub-analysis were symptomatic participants enrolled in a case-control study in a laboratory setting in an academic medical center. Sample size was determined by a primary aim of the case-control study (hip external rotation strength differences between cases and controls). Twenty-one participants with UF-LUTS were recruited from the community between April and December 2019. Female participants age 18-60 were included if they experienced bothersome urinary urgency and/or frequency at least sometimes in the past 4 weeks, as reported during a phone screen. Participants with stress or mixed urinary incontinence, current or recurrent urinary tract or gynecologic infection or
cancer, or symptomatic pelvic organ prolapse were excluded. Full exclusion criteria are available in Chapters 2 and 3 of this dissertation.

A.3.2 Musculoskeletal Variable Selection

Based on the case-control studies outlined in Chapters 2 and 3, one variable for each construct was chosen based on those with the largest effect sizes between cases and controls: for hip strength, hip external rotation force (Cohen’s d=0.60); for PFM mobility, puborectalis (PR) length excursion to bear down (d=0.43); and for PFM position, Levator plate angle (LPA) at rest (d=0.67). PFM strength was omitted from this analysis due to small effect size in case-control analysis (d=0.22).

A.3.3 Musculoskeletal Variable Measurement Methods

Full detailed measurement methods for hip external rotation strength are available in Chapter 2, and for PR length and LPA in Chapter 3. Hip external rotation strength was measured via isometric dynamometry, seated in neutral rotation. The hip external rotation strength variable represents the mean of participants’ right and left side peak force output in Newtons. PR length and LPA were captured via dynamic 2-D transperineal ultrasound as saved videos of a PFM movement sequence including resting and bearing down. Measurements were made offline from static frames at rest and peak bearing down. PR length excursion to bear down represents the length in millimeters from pubis to the anorectal junction, with the measurement at rest subtracted from the measurement at bearing down. A positive value represents muscle lengthening. The levator plate angle is measured in degrees, vertex at the
posterior-inferior pubis, with one side as a reference line perpendicular to the transducer and the other side from pubis to anorectal junction. A larger LPA represents a more cranial and anterior position at rest, while a smaller LPA represents a more caudal and posterior position at rest.

A.3.4 UF-LUTS Symptoms, Bother and Impact on Quality of Life

Prior to physical examination, participants completed questionnaires on REDCap electronic data capture tools. For this sub-analysis, storage symptoms and bother were assessed via the LUTS Tool. Storage LUTS symptom and bother subscales, the portion of the LUTS Tool most reflective of UF-LUTS, were summed. The impact of participants’ urogenital symptoms on their quality of life was assessed with the Pelvic Floor Impact Questionnaire short form urogenital subscale (UIQ).

A.3.5 Statistical Analysis

Statistical analyses were computed using SPSS Version 25.0 (IBM Corp, Armonk, NY). Among women with UF-LUTS, correlation coefficients with two-tailed tests of significance and bivariate plots were used to assess the association between each musculoskeletal variable with the LUTS Tool storage subscale and the UIQ. Assumptions were checked graphically with histograms and Q-Q plots and statistically with the Shapiro Wilk test. Where Pearson correlation assumptions were violated, Spearman’s Rank correlation coefficients are reported.
A.4 RESULTS

None of the musculoskeletal variables examined were associated with storage LUTS or quality of life (TABLE A.1, FIGURE A.1).

<table>
<thead>
<tr>
<th>Table A.1</th>
<th>Associations between musculoskeletal variables and LUTS symptoms and quality of life among women with urgency and frequency predominant LUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUTS Tool</td>
<td>Storage Subscale</td>
</tr>
<tr>
<td></td>
<td>$r$</td>
</tr>
<tr>
<td>Hip External Rotator Strength</td>
<td>0.25</td>
</tr>
<tr>
<td>PR length excursion to bear down*</td>
<td>-0.24</td>
</tr>
<tr>
<td>LPA at rest</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Spearman's rank correlation coefficient, others Pearson correlation coefficients

LUTS= Lower Urinary Tract Symptoms; PFIQ-7 UIQ = Pelvic Floor Impact Questionnaire Short Form 7 Urogenital Subscale; PR = puborectalis; LPA = levator plate angle

A.5 DISCUSSION

Contrary to our hypothesis, hip strength, PFM mobility, and PFM position were not associated with LUTS symptoms and quality of life among women with UF-LUTS. These results contrast with our case-control results which found decreased hip strength, decreased PFM mobility, and elevated resting PFM position in women with UF-LUTS compared to controls.
A.5.1 Study Limitations

We may not have detected associations because the range in our participants’ questionnaire scores represents mild-moderate symptom, bother and impact on quality of life. There may not have been a wide enough range to detect an association between these scores and our musculoskeletal variables. On visual inspection of the scatterplots for the association between hip strength and UIQ, one might see a potential for a relationship in the opposite direction as our hypothesis. I postulate that this is a random occurrence and would look differently given greater range in participants’ UIQ scores.

A.6 CONCLUSIONS

We found no associations between selected musculoskeletal variables and storage LUTS and their impact on quality of life among women with UF-LUTS. However, this analysis was underpowered. A larger study with greater range in participants’ severity of symptoms, bother and impact on quality of life may be more informative.
FIGURE A.1 Scatterplots showing musculoskeletal variables and questionnaire scores among women with UF-LUTS

LUTS Storage Subscale obtained from summing storage symptoms and bother. 0=no symptoms/bother, 35=maximum. PFIQ-7 UIQ scale 0=no urogenital impact on quality of life, 100 = maximum. LPA at Rest – larger angles indicate more cranial/anterior position of the pelvic floor. PR Length Excursion – more positive values indicate muscle lengthening; negative indicate muscle shortening.
A.7 REFERENCES


Appendix B:

Static Ankle Dorsiflexion and Hip and Pelvis Kinematics during Forward Step-Down in Patients with Hip-Related Groin Pain

This work has been accepted for publication and is included with permission of the journal.

B.1 ABSTRACT

**Context:** We hypothesized that in people with hip-related groin pain, less static ankle dorsiflexion could lead to compensatory hip adduction and contralateral pelvic drop during step-down. Ankle dorsiflexion may be a modifiable factor to improve ability in those with hip-related groin pain to decrease hip/pelvic motion during functional tasks and improve function.

**Objective:** To determine whether smaller static ankle dorsiflexion angles were associated with altered ankle, hip and pelvis kinematics during step-down in people with HRGP.

**Design:** Cross-sectional

**Setting:** Academic Medical Center

**Patients:** Thirty people with hip-related groin pain (12M,18F; 28.7±5.3y) participated.

**Intervention:** None.

**Main Outcome Measures:** Weight-bearing static ankle dorsiflexion with knee flexed and knee extended were measured via digital inclinometer. Pelvis, hip, and ankle kinematics during forward-step-down were measured via 3D motion capture. Static ankle dorsiflexion and kinematics were compared with bivariate correlations.

**Results:** Smaller static ankle dorsiflexion angles were associated with smaller ankle dorsiflexion angles during the step-down for both the knee flexed and knee extended static measures. Among the total sample, smaller static ankle dorsiflexion angle with knee flexed was associated with greater anterior pelvic tilt and greater contralateral pelvic drop during the step-down. Among only those who did not require a lowered step for safety, smaller static ankle dorsiflexion angles
with knee flexed and knee extended were associated with greater anterior pelvic tilt, greater contralateral pelvic drop and greater hip flexion.

**Conclusions:** Among those with hip-related groin pain, smaller static ankle dorsiflexion angles are associated with less ankle dorsiflexion motion and altered pelvis and hip kinematics during a step-down. Future research is needed to assess the effect of treating restricted ankle dorsiflexion on quality of motion and symptoms in patients with hip-related groin pain.
B.2 BACKGROUND

Hip-related groin pain (HRGP) results in significant pain and activity limitations among young to middle aged adults. Hip disorders proposed to contribute to HRGP include femoroacetabular impingement syndrome (FAIS), acetabular dysplasia, labral tears and injury to other intra-articular structures. Poor quality of movement (specifically hip adduction and contralateral pelvic drop) have been associated with lower extremity pain and injury.\(^1\)–\(^4\) Therefore, hip and pelvic motion may represent modifiable factors amenable to intervention aimed at reducing hip joint damage, decreasing HRGP, and improving patient function.

Our previous clinical trial of physical therapist-led intervention for HRGP investigated movement pattern training to improve kinematics during lower extremity movement. People with HRGP were able to reduce hip adduction motion during a single limb task\(^5\) and this reduction was associated with improved patient-reported function.\(^5,6\) It has been suggested that increased hip adduction motion and/or contralateral pelvic drop may occur due to weakness in hip or trunk muscles, but previous studies have shown that hip abductor and external rotator muscle strength are not associated with hip adduction motion during single-leg activities.\(^7\)–\(^10\) Therefore other factors must be considered.

A limitation in ankle dorsiflexion (ADF) is one potential factor that may contribute to poor quality of hip and pelvic movement. Limited available ADF may lead to compensatory proximal motion including hip adduction and contralateral pelvic drop. Smaller ADF angles have been associated with larger hip adduction angles and/or contralateral pelvic drop in healthy people\(^11\)–\(^14\) and people with knee pain\(^15\) across various single- and double-limb tasks, but the role of ADF on hip movement has not been studied among people with HRGP. If found to be associated with
abnormal hip/pelvic motion, ADF may represent a modifiable factor to improve function in people with HRGP.

The purpose of this experiment was to determine whether smaller static ADF angles were associated with altered ankle, hip and pelvis kinematics during step-down in people with HRGP. We chose a step-down as a simulation of functional step descent that requires a substantial degree of ADF motion. We hypothesized that smaller static ADF angles, particularly with the knee flexed, would be correlated with smaller ADF angles, greater hip adduction angles and contralateral pelvic drop assessed during the step-down task.

B.3 METHODS

B.3.1 Design

This was a cross-sectional study designed to use baseline data from a pilot multisite randomized clinical trial for patients with HRGP. Only patients enrolled at the Washington University site were included in the current study as additional funding allowed for collection of 3D kinematic data. Data collection occurred at The Movement Science Research Center at Washington University in St. Louis, Missouri. The study was approved by the Human Research Protection Office at Washington University in St. Louis and informed consent was obtained prior to participation.
B.3.2 Participants

Thirty participants (12 male, 18 female) were enrolled and completed testing. Demographics are described in TABLE B.1. Patients were recruited between January 2017 and February 2018, from healthcare clinics; research volunteer databases; public service announcements using newspaper, social media, and other written communications. Study participants were 15-40 years old; reported deep hip joint or anterior groin pain that was reproduced with a flexion, adduction, internal rotation impingement test (FADIR), reported pain $\geq 3/10$ and present $>3$ months; and demonstrated functional limitation with modified Harris Hip Score $<90$. Exclusion criteria included previous hip surgery, fracture, infection, or pain due to high impact trauma; diagnosed with Legg-Calve-Perthes Disease or slipped capital femoral epiphysis; inflammatory disease; neurological involvement affecting balance; pain, numbness or tingling that radiates into thigh; known pregnancy; and screening tests indicating hip joint pain was referred from the spine. Prior to the laboratory testing, participants completed questionnaires related to their symptoms (Hip Disability and Osteoarthritis Outcome Score (HOOS) and numeric pain rating scale) and activity levels (University of California, Los Angeles (UCLA) activity scale).

B.3.3 Procedures

B.3.3.1 Ankle Dorsiflexion Range of Motion Measurement

After a 5-minute warm-up of walking on a treadmill, static ADF was measured with a digital inclinometer (microFET3, Hogan Health Industries, Salt Lake City, UT, USA) in weightbearing both with the knee extended (FIGURE B.1A) and the knee flexed (FIGURE B.1B). On the tested
leg, a vertical line was drawn bisecting the calcaneus (to estimate the medial-lateral center of the calcaneus) and a mark was drawn on the anterior tibial border, 15 cm distal to the tibial tuberosity. Participants were permitted to hold on to a bar during the test and to rest the untested leg in a comfortable position on the floor to maintain balance. Participants positioned their test foot so that the center of the calcaneus and first toe aligned with a line on the floor that was perpendicular to the bar. The inclinometer was zeroed to a vertical reference, then placed at the mark on the anterior tibial border to capture the tibial angle. The heel of the tested leg was not permitted to lift from the floor during the test. Two measurements were taken in each of the following positions, with 15 seconds rest between measurements: with the test knee fully extended (FIGURE B.1A) and with the test knee flexed to at least 20 degrees (FIGURE B.1B). Inclinometer readings were recorded in degrees. If the two measurements taken for a position were more than 5 degrees apart, a 3rd measurement was taken. Instructions to the participant were as follows: “Maintain the entire foot touching the ground and straight forward as it is now. Move your pelvis forward toward the wall until your heel wants to lift off the ground.”

Figure B.1. A. Static Ankle Dorsiflexion with knee extended, B. Static Ankle Dorsiflexion with knee flexed
B.3.3.2 Three-dimensional Motion Capture

During the step-down, three-dimensional kinematic variables for the lower extremities were captured using a 10-camera motion capture system (Vicon Nexus, Denver, CO, USA). Retroreflective markers were placed on anatomical landmarks representing the pelvis, femur, shank and foot (FIGURE B.2). A static calibration trial was conducted prior to step-down trials.

![Figure B.2. Markers for the pelvis included bilateral anterior and posterior superior iliac spines; for the thighs included lateral femoral epicondyles, rigid four-marker clusters, and a regression-based virtual hip joint center marker19; for the lower legs included the tibial tuberosities, rigid four-marker clusters and medial/lateral malleoli; for the rearfoot included the center of the posterior calcaneus inferiorly and superiorly, the sustentaculum tali and the peroneal tubercle. Markers on the medial epicondyles and medial malleoli were used for a calibration trial only and removed for motion trials. Additional markers on the distal foot were not included in analysis.]

B.3.3.3 Step-down

Step height was selected according to participant height: 15.2 cm for height <163 cm, 20.3 cm for height 163 - 180 cm and 25.4 cm for height >180 cm. Study piloting revealed using the same standard step height for all participants was not challenging enough for taller participants and too
challenging for shorter participants (unable to complete without loss of balance), and thus, the height-dependent protocol was developed for and used in a previous study. Participants were instructed to place arms across chest and step forward off the step with their opposite limb, “tap” the floor lightly with their heel, then return to bilateral stance on the step (FIGURE B.3). Participants practiced the step-down tap until they were comfortable with performing the motion. If the participant was unable to tap the floor with their heel without a loss of balance, the step was lowered to the next discrete height they could perform the task successfully. Three successful trials were captured for analysis.

Figure B.3 Step-down task
B.3.3.4 Kinematic Data Processing

Kinematic data were processed using Visual 3D software (C-Motion Inc, Germantown, MD). A six-degrees-of-freedom model was used for the pelvis and thigh (three independent translational degrees-of-freedom (position) and three independent rotational degrees-of-freedom (orientation). The hip joint center was defined using a Harrington Equation 2 hip joint center. The rearfoot and ankle joint center followed the modified Oxford model. Pelvis angles were defined relative to the lab coordinate system. Hip angles were defined as thigh relative to pelvis and ankle angles were defined as rearfoot relative to lower leg. Joint angles at peak of the step-down motion (at heel tap) were averaged between the three motion trials for analysis.

B.3.4 Statistical Analysis

Analysis is based on the participants’ self-selected most bothersome hip (test hip) and the ipsilateral ankle. Because ten of our participants required a lower-than-prescribed step height to complete a valid step-down trial, we ran all analyses for both the full sample of n=30 and the n=20 who performed on the initially prescribed step height. Normality of all variables was assessed graphically with Q-Q plots and with the Shapiro-Wilk test. Outliers greater than 1.5 times the interquartile range were examined. Equality of variance was assessed with Levene’s test. Pearson correlation coefficients were used to assess the relationships between static ADF and kinematic variables. When Pearson correlation assumptions were violated, Spearman’s rank correlation coefficients are reported. A P value less than .05 was considered significant. Confidence intervals (95% CI) were computed around the correlation coefficient magnitudes to demonstrate the gestalt of correlation estimates across the sample of n=30 and n=20 for both
knee flexed and knee extended static ADF conditions. Characteristics and descriptive statistics were compared using independent t-tests except for age, body mass index (BMI), HOOS Activities of Daily Living Subscale, average pain, and UCLA (Mann-Whitney U Test). Analyses were run in IBM SPSS Statistics version 25 (IBM Corporation, Armonk, NY).

B.4 RESULTS

Participant characteristics are provided in Table B.1.

B.4.1 Correlations: Static ADF and ankle ADF motion

Smaller static ADF angles were associated with smaller ADF angles during the step-down among the total sample and among those who performed on the prescribed step, for both the knee flexed and knee extended static ADF measure (TABLE B.3). Confidence intervals around the magnitude of correlation coefficients demonstrate this relationship consistently under all conditions.
### Table B.1. Participant characteristics mean ± standard deviation

<table>
<thead>
<tr>
<th></th>
<th>All, n=30</th>
<th>Prescribed Step, n=20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28.7 ± 5.3</td>
<td>27.6 ± 5.2</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>25.0 ± 5.8</td>
<td>23.0 ± 2.4</td>
</tr>
<tr>
<td>Sex (% Female)</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>HOOS Symptom Subscale</td>
<td>69.5 ± 14.0</td>
<td>68.5 ± 13.3</td>
</tr>
<tr>
<td>HOOS Pain Subscale</td>
<td>73.3 ± 10.2</td>
<td>72.5 ± 9.5</td>
</tr>
<tr>
<td>HOOS Activities of Daily Living Subscale</td>
<td>87.3 ± 9.4</td>
<td>87.5 ± 8.2</td>
</tr>
<tr>
<td>HOOS Sports &amp; Recreation Subscale</td>
<td>68.1 ± 17.2</td>
<td>67.2 ± 14.0</td>
</tr>
<tr>
<td>HOOS Quality of Life Subscale</td>
<td>57.1 ± 14.2</td>
<td>57.5 ± 14.7</td>
</tr>
<tr>
<td>Average Pain in Past Week</td>
<td>3.1 ± 1.3</td>
<td>3.0 ± 1.1</td>
</tr>
<tr>
<td>Worst Pain in Past Week</td>
<td>5.2 ± 1.7</td>
<td>4.9 ± 1.6</td>
</tr>
<tr>
<td>UCLA Activity Score</td>
<td>10 (4-10)</td>
<td>10 (4-10)</td>
</tr>
</tbody>
</table>

* HOOS Subscales: 100=no disability

* Numeric Pain Rating Scale, 0= no pain, 10 = worst pain imaginable

* UCLA Activity Score Median (Minimum-Maximum); 0 = wholly inactive..., 10 = regular participation in impact sports.

### Table B.2. Descriptive statistics for mean ± SD of kinematic variables

<table>
<thead>
<tr>
<th></th>
<th>All, n=30</th>
<th>Prescribed Step, n=20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angles (degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static ADF with Knee Flexed</td>
<td>42.2 ± 7.9</td>
<td>44.6 ± 7.0</td>
</tr>
<tr>
<td>Static ADF with Knee Extended</td>
<td>36.5 ± 6.6</td>
<td>38.6 ± 5.2</td>
</tr>
<tr>
<td>3D Pelvis Anterior Tilt</td>
<td>22.2 ± 7.0</td>
<td>22.2 ± 6.9</td>
</tr>
<tr>
<td>3D Pelvis Obliquity - Contralateral Drop</td>
<td>-8.7 ± 4.0</td>
<td>-9.6 ± 4.0</td>
</tr>
<tr>
<td>3D Pelvis Rotation - Toward Stance Leg</td>
<td>-9.6 ± 0.6</td>
<td>-10.4 ± 5.4</td>
</tr>
<tr>
<td>3D Hip Flexion</td>
<td>61.9 ± 11.6</td>
<td>64.1 ± 11.6</td>
</tr>
<tr>
<td>3D Hip Adduction</td>
<td>20.3 ± 4.5</td>
<td>20.8 ± 4.4</td>
</tr>
<tr>
<td>3D Hip Internal Rotation</td>
<td>4.3 ± 8.8</td>
<td>2.0 ± 7.4</td>
</tr>
<tr>
<td>3D Ankle Dorsiflexion</td>
<td>26.7 ± 5.6</td>
<td>28.0 ± 5.7</td>
</tr>
</tbody>
</table>

Landmark excursion (centimeters)

|                          |           |                       |
| Heel lift                | 1.9 ± 1.8 | 1.7 ± 1.3             |
### TABLE B.3, Correlation coefficients (95% confidence interval) between Static Ankle Dorsiflexion and 3D Joint Angles and Landmark excursion

<table>
<thead>
<tr>
<th>Angles (degrees)</th>
<th>All, n=30</th>
<th>Participants on Prescribed Step Height, n=20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static ADF with Knee Flexed</td>
<td>Static ADF with Knee Extended</td>
</tr>
<tr>
<td></td>
<td>r (95% CI of r)</td>
<td>P</td>
</tr>
<tr>
<td>Pelvis Anterior Tilt</td>
<td>-.42 (-.67, -.06)</td>
<td>.023</td>
</tr>
<tr>
<td>Pelvis Obliquity&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.44 (.09, .68)</td>
<td>.015</td>
</tr>
<tr>
<td>Pelvis Rotation&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.02 (-.34, .37)</td>
<td>.929</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>-.27 (-.57, .09)</td>
<td>.143</td>
</tr>
<tr>
<td>Hip Adduction</td>
<td>-.21 (-.53, .16)</td>
<td>.260</td>
</tr>
<tr>
<td>Hip Internal Rotation</td>
<td>.14 (-.23, .47)</td>
<td>.477</td>
</tr>
<tr>
<td>Ankle Dorsiflexion</td>
<td>.60 (.30, .78)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Landmark excursion (centimeters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heel lift&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-.35 (-.63, .01)</td>
<td>.056</td>
</tr>
</tbody>
</table>

<sup>a</sup> Larger contralateral pelvic drop correlates with smaller ADF angle

<sup>b</sup> Spearman's rank correlation coefficient, all others Pearson

Bolded: correlation is significant at the .05 level (two-tailed)
B.4.2 Correlations: Static ADF and hip/pelvis motion

Among the total sample, smaller static ADF with knee flexed was associated with greater anterior pelvic tilt and greater contralateral pelvic drop during the step-down. Among only those who performed on the prescribed step, smaller static ADF angle with knee flexed and knee extended was associated with greater anterior pelvic tilt, greater contralateral pelvic drop and greater hip flexion (TABLE B.3). Confidence intervals around the magnitude of correlation coefficients of these relationships under all conditions are presented in TABLE B.3. Representative scatter plots are provided in FIGURE B.4.
B.5 DISCUSSION

This study demonstrates smaller static ADF angles measured in weight bearing is associated with smaller ADF angles and altered pelvis and hip kinematics during a step-down. These altered kinematics may represent proximal compensations for limited ADF. Most predictably in our sample, compensations for limited ADF were contralateral pelvic drop and/or anterior pelvic tilt. People with HRGP may have difficulty improving their hip and pelvis movement patterns during
challenging functional and fitness tasks if ADF is limited. We have previously shown that targeting hip and pelvic movement patterns results in improved function for some people.\textsuperscript{5,6} For those with HRGP, optimizing functional movement pattern training outcomes may need to include treatment to address ADF limitations.

Evidence is limited linking static ADF and 3D kinematics of the pelvis and hip. The relationship between static ADF and contralateral pelvic drop or hip adduction, to our knowledge, has not been studied in people with HRGP. Few studies report ankle and pelvic motion together, and we found only one reporting pelvic motion during forward step-down.\textsuperscript{13} Lebleu et al.\textsuperscript{13} compared healthy participants stepping down with the stance foot flat on the step vs stance forefoot elevated 2 cm, placing the ankle in greater dorsiflexion at start of the task, thus reducing the dorsiflexion excursion available for task completion. They found that when available dorsiflexion motion was reduced by elevating the forefoot, contralateral pelvic drop and hip adduction were both significantly increased compared to the normal foot position. These results are consistent with our findings that limited ADF may contribute to compensatory movements more proximally at the pelvis. In the absence of sufficient ADF to aid in lowering the center of gravity, perhaps people compensate to lower the non-weightbearing limb via contralateral pelvic drop or anterior pelvic tilt.

Our study did not find a statistically significant relationship between smaller static ADF angle and hip adduction motion during the step-down. It is possible that we may have seen an association between smaller static ADF angles and larger hip adduction angles in a larger sample with a strict protocol that ensures all participants are maximally challenged in their ADF, regardless of their balance and neuromotor control. Multiple studies in healthy people\textsuperscript{14,15,22–26} and people with knee pain\textsuperscript{15} have demonstrated a relationship between smaller ADF angles and
greater hip adduction motion or medial knee deviation during single-limb tasks. Direct comparison to the previous studies is difficult due to differences in the measurement methods used, the task assessed, and the population included. One study by Rabin et al., with measurement methods similar to ours (weightbearing static ADF and kinematic analysis of hip adduction), assessed a lateral step-down performed by healthy participants and reported significantly greater hip adduction in a subset with low static ADF compared to the subset with high ADF. The difference between our findings and those of Rabin et al., may be related to the task performed as pelvic and hip motion has been shown to vary between single leg tasks, and ankle motion may vary between tasks. Additionally, healthy participants without HRGP may adopt different compensatory patterns compared to those with HRGP.

We measured static ADF with knee flexed in addition to ADF with knee extended, given that the forward step-down requires knee flexion. We found no previous studies that measured static ADF with knee flexed and pelvis motion together. The magnitude of correlation coefficients with kinematic variables were similar when comparing knee flexed and knee extended static ADF measures. Static measures with knee flexed were greater than with knee extended (TABLE B.2) and each yields novel clinical information that may inform treatment (flexed-knee ADF provides information about soleus or ankle joint limitation, while extended-knee ADF provides information about gastrocnemius limitation). However, a simple screen to determine whether ADF limitation is at issue for a patient with HRGP may be most efficient by choosing one static measure. A larger sample size is warranted before discounting the importance of either static ADF measure for patients with HRGP.
Interestingly, one third of our participants (4 females, 6 males) required a lower step height than the one specified by their body height. This provision allowed all participants to safely complete three valid step-down trials. Those who performed on the prescribed step were not substantially different from the total sample in terms of their characteristics (TABLE B.1) or kinematic variables (TABLE B.2). However, associations between static ADF and several hip and pelvis kinematic variables were stronger for the 20 participants on the prescribed step height (TABLE B.3). Forty percent of our participants (n=12) performed on a step height lower than standard for most building codes in the United States (allowing up to 19.7cm). Based on our sample estimates, 40% of people with HRGP may not be able to descend a regulation staircase without altered pelvis motion. Therefore, assessment and functional training is warranted to ensure patients with HRGP have the capacity of ADF motion, balance, and neuromotor control to step-down during daily activities without compromising their hip and pelvis motion.

Our study demonstrates that static measures of ADF are related to ankle, pelvis and hip motion during functional activity in people with HRGP, suggesting utility of improving ADF in an effort to improve quality of functional movement. One small study in asymptomatic males with ADF asymmetry tested step-down before and immediately after ankle joint mobilizations. In their study, although ADF significantly improved after mobilizations, ankle, pelvis and hip step-down kinematics did not change immediately post-mobilization. Perhaps a longer-term intervention to improve ankle dorsiflexion combined with movement pattern training is needed to reap the benefit of ADF gains during functional tasks. Interventions to improve ankle dorsiflexion may include static or proprioceptive neuromuscular facilitation stretching, self-myofascial release, joint mobilizations, and/or eccentric plantar flexor strengthening, but these interventions have
not been studied for comparative long-term effectiveness, nor their influence on proximal
biomechanics. A larger study, testing a long-term intervention and follow-up, is warranted.

B.5.1 Limitations

These results may be specific to young and middle-aged adults with HRGP and may not be
generalizable to all with hip conditions. Three participants lifted the heel on the stance leg during
the step-down greater than 3.7cm (1 standard deviation from the mean heel lift). Post hoc
analysis revealed those who lifted the heel greater than 3.7cm demonstrated insignificantly
smaller ADF motion during stepdown compared to those with less than 3.7cm heel lift (21.7 ± 5.7 cm vs 27.3 ± 5.5 cm, \(P=.11\)). The quantity of heel lift across all participants was not
significantly associated with any of our variables of interest. Also, omitting these three
participants did not significantly alter the correlation coefficients or study conclusions; thus, we
believe the continuum of heel lift reflects a diversity in motor performance. Two participants’
BMI was over 30kg/m². As BMI increases, so increases marker motion related to tissue
movement and unrelated to segmental motion associated with the task. The parent study did not
have a BMI exclusion and thus all 30 participants participated in motion capture. None of the
above participants were statistical outliers for any variable and qualitative visual appraisal of
their data did not appear outside of expected.
B.6 CONCLUSION

Among those with HRGP, smaller static ADF angles are associated with smaller ADF motion and altered pelvis and hip kinematics during a step-down. Future research is needed to assess the effect of treating restricted ADF on quality of motion and symptoms in patients with HRGP.
B.7 REFERENCES


doi:10.2519/jospt.2018.7810

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B.8 FUNDING AND ACKNOWLEDGEMENTS

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Public Trials Registry ClinicalTrials.gov Identifier: NCT02913222

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