SACROILIAC JOINT DYSFUNCTION

Is fusion the solution?

Sem M.M. Hermans

Sacroiliac joint dysfunction:

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Publication of this thesis was supported by Dutch Spine Society, Julie Hoofwijk Fonds, IN2MED, Maastricht University, Nederlandse Orthopaedische Vereniging, ABN AMRO and Zuyderland Academie. Their financial support is gratefully acknowledged.

Design: Valérie Schuermans
Lay-out: Tiny Wouters
Print: ProefschriftMaken | www.proefschriftmaken.nl
ISBN: 978-94-6469-895-4

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PROEFSCHRIFT

Voor het behalen van de graad van doctor aan de Universiteit Maastricht,

in opdracht van Rector Magnificus, Prof. dr. Pamela Habibović,

overeenkomstig met het besluit van het College van Decanen,

te verdedigen in het openbaar op

maandag 27 mei 2024 om 10:00 uur

door

Sem Markus Maria Hermans

Promotor

Prof. dr. H. van Santbrink, Universiteit Maastricht

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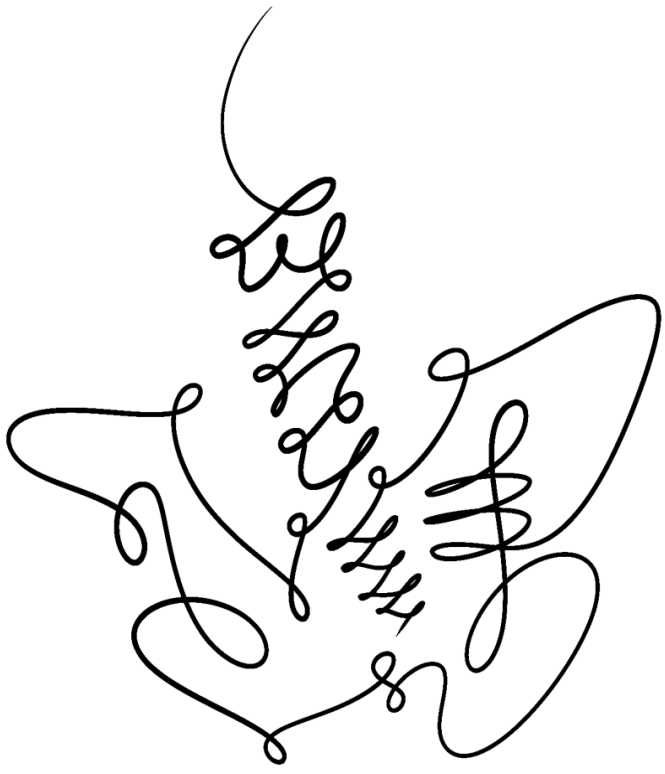
Table of contents



Chapter 1

General introduction

General introduction

Low back or buttock pain continues to be a major health concern with a global lifetime prevalence of 70-80%.[1] Low back complaints are the leading cause of activity limitation, absenteeism from work and disability-adjusted life years globally, resulting in major medical burden and economic cost.[2,3] Only 20 to 30% of low back complaints can be attributed to specific causes, in the majority of cases the cause remains unclear.[4] Sacroiliac joint (SIJ) dysfunction is an underappreciated source of low back or buttock pain, with an incidence estimated to be as high as 25% in individuals with these complaints.[5,6]

The SIJ is the largest axial joint of the body and shaped by the sacrum and pelvis (Figure 1.1).[7] The bony anatomy is highly variable in size, shape and contours among individuals.[8] A fibrous capsule between the articular surfaces surrounds the joint area filled with synovial fluid.[9] The articular surface changes from infancy to adulthood. Generally, the articular part consists of two C-shaped layers of which the sacral part is concave and the iliac part is predominantly convex. The surface of the SIJ can be divided into three parts, roughly corresponding to the three sacral elements (S1, S2, S3) that contribute to the sacral articular surface.[8] The SIJ is well innervated, however the patterns of innervation varies among individuals. Most innervation is derived from the sacral dorsal rami (L5-S1).[10]

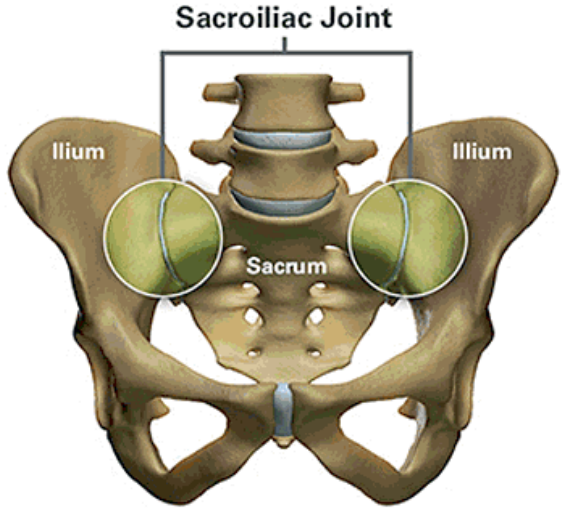


Figure 1.1 Schematic overview of SIJ anatomy. *Source: https://si-bone.com. Obtained written permission to use image.*

The primary function of the SIJ is to attenuate the distribution of force loads to the lower extremities.[11] Vleeming et al. adapted the concept of form and force closure to the SIJ, which described the dynamics and mechanical aspects of the joint.[12] Form closure results in a theoretically stable setting with joint surfaces that fit closely. One can compare this mechanism to the fit of interlocking toy blocks. However, maintaining perfect form closure restricts SIJ mobility, which is essential for daily life activities. In addition to form closure, force closure is required to withstand high vertical shear forces and loads. Force closure occurs because of altered joint reaction force via taut ligaments, fascia, muscles, and the ground reaction force. This results in a perpendicular compressive reaction force to the SIJ.[7] Combined with several complex sacral ligamentous structures and muscles, including the gluteus maximus and piriformis, the SIJ is supported and re-enforced. The magnitude of the range of motion of the SIJ has been studied extensively and is typically defined to 2 to 4 mm and 2 to 5 degrees of rotation and translation.[13,14] The sacrum can move in all directions with respect to the ilium and the primary plane of motion is from anterior to posterior along the transverse axis.

Although SIJ motion is limited, several conditions can lead to SIJ dysfunction. A wide variability exists in clinical presentation, from localized pain around the SIJ to radiating pain into the groin or even the entire lower extremity.[15] It is thought that individual differences in innervation of the SIJ accounts for the variable presentation of (referred) pain.[14] Patients often describe pain being present or aggravated by prolonged standing or sitting, walking or by getting out of a chair. Another common complaint is the perception of instability in the pelvic area or leg, also known as giving way.[16] The symptomatology largely overlaps with other orthopedic disorders such as lumbar degenerative disc disease and degenerative hip disease. SIJ dysfunction is often overlooked as a potential cause for chronic complaints in the lower back and buttocks.[17] As a result, it is under diagnosed and subsequently under treated.[18] Patients with undiagnosed SIJ dysfunction might therefore represent a significant number of chronic pain patients with an unrevealing spine evaluation. Patients eventually diagnosed with SIJ dysfunction often feel misunderstood as their symptoms were dismissed or ignored for a long time. These patients report a low quality of life, comparable to that of patients with degenerative spondylolisthesis, spinal stenosis, and intervertebral disc herniation.[19] The underlying mechanism of SIJ dysfunction varies and are elaborated below.

Posttraumatic

SIJ dysfunction may be caused by injury to the supporting ligaments or the joint itself. In most traumatic cases, the cause is a high impact trauma or repetitive trauma, such as weightlifting or other sports.[20] Trauma in the context of pelvic ring injuries is frequently accompanied with SIJ injury. When pelvic ring fractures are accompanied with SIJ disruption, operative anatomical reduction of the SIJ should be strived for, as better anatomic reduction results in better long-term clinical outcome.[21]

Degenerative

Osteoarthritis of the SIJ is common and the incidence increases with age.[22,23] Related anatomical abnormalities may also play a role in the development of degenerative dysfunction. Altered gait, spinal deformities or leg-length discrepancies can reduce the interlocking ability of the joint, resulting in laxity and pain. This relates to repetitive and uneven stress to the SIJ leading to accelerated degeneration. Nonetheless, caution must be taken when attributing lower back pain to SIJ degeneration, as it is highly prevalent in asymptomatic individuals.[24]

Postpartum

During pregnancy the ligamentous apparatus of the SIJ loosens with the presence of hormonal factors, such as relaxin and estrogen.[25] This provides an increase in joint mobility, which can finally result in persistent SIJ dysfunction. Other predisposing factors in the development of postpartum SIJ dysfunction are the increase in weight, change in posture and increased abdominal pressure. Pain during pregnancy in the SIJ, pubic symphysis or lumbosacral region is often referred to as pelvic girdle pain (PGP). Almost 50% of women experience some sort of PGP during and following pregnancy. In most cases the pain resolves within four months after giving birth, but in roughly 20% of patients pain persists.[23,26]

Post lumbar fusion surgery

The prevalence of SIJ dysfunction is increased in patients who previously underwent lumbar fusion surgery.[27] Degeneration in segments above or below a fused spinal segment, accompanied with new onset of complaints, is known as adjacent segment disease.[28] The phenomenon has been extensively described in

the literature and is nowadays considered to be a potential long-term complication of fusion surgery. After lumbar fusion surgery it is believed that mechanical load is transferred from the lumbar segments on the SIJ. This additional load may cause accelerated degeneration, potentially compromising form closure. Consequently, the ability of the SIJ to attenuate the distribution of force loads is disturbed, potentially resulting in dysfunction.[29]

Connective tissue disorders

Another possible entity of SIJ dysfunction are connective tissue disorders, such as Ehlers-Danlos syndrome (EDS). EDS is a group of hereditary disorders that affects connective tissues, primarily skin, ligaments, joints and blood vessel walls.[30] Variations in genes alter the structure, production, or processing of collagen, resulting in weakened connective tissue. The latter may result in hypermobility in ligaments surrounding the SIJ. Consequently the SIJ destabilizes, compromising the force closure mechanism. The increased motion in the joint is believed to cause dysfunction and complaints.[31,32]

Diagnosing SIJ dysfunction

People with SIJ dysfunction often describe pain that extends from the lower back to the buttock and down the thigh. Persistent discomfort is frequently experienced when bearing weight on the affected side during activities like sitting or walking, and even while lying in bed. This often results in compromised gait, balance, and overall well-being.[33] As a result, these individuals frequently face challenges with sleeping and changing positions. The pain associated with SIJ dysfunction is specifically localized inferior and medial to the posterior superior iliac spine. When patients pinpoint this area as the main source of pain, it is considered a positive result in the Fortin finger test.[34] Physicians can also palpate the SIJ to determine the area of tenderness. Functional tests may also be performed to assess gait and gluteal weakness (Trendelenburg).[34] Several provocative tests are described in the literature, but reliability and validity are limited.[35,36] This is most likely because of the limited range of motion of the joint, and because loading the SIJ will stress surrounding structures.[15] The most common provocative tests are described below (Figure 1.2).

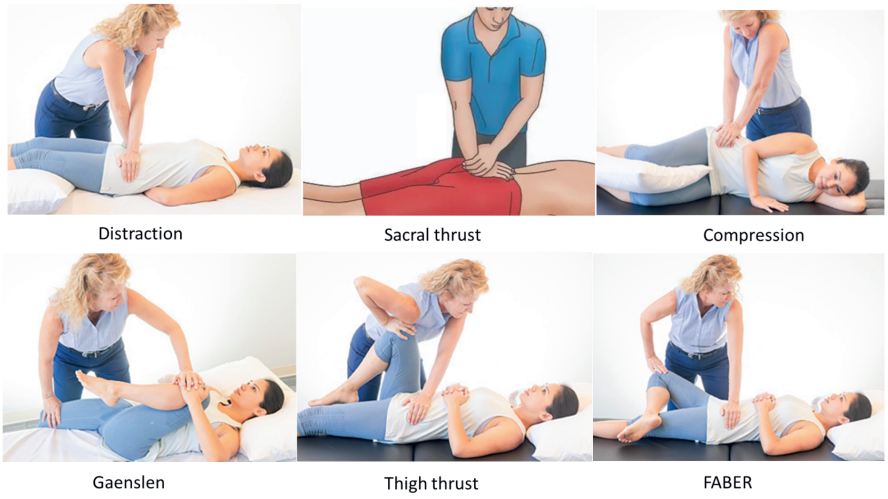


Figure 1.2 The six pain provocation positions are depicted from left to right; distraction position, sacral thrust position, compression position, Gaenslen's position, thigh thrust position and FABER position. *Source: https://si-bone.com and Master thesis V.M.J. Helgers: Development of a 3D CT stress test method for assessment of sacroiliac joint motion in clinical positions using image registration: A proof of concept study. Obtained written permission to use image.*

Distraction test

The patient is positioned supine. Outward rotatory stress on both the anterior superior iliac spine (ASIS) is applied. Intensified pain in the SIJ region is suggestive of SIJ dysfunction.[23]

Sacral thrust

The patient lies in prone position. Downward pressure is exerted on the sacral base. This maneuver stretches the ligaments of the SIJ, causing compression in both joints. The test yields a positive result if pain is experienced during this procedure.[23]

Compression test

The patient is positioned on the side. A downward directed compression force is applied to the top of the iliac crest. The occurrence of pain in the SIJ region during this test suggests the possibility of SIJ dysfunction.[23]

Gaenslen's test

The patient is positioned supine. The contralateral hip and knee are flexed towards the patient's chest while the opposite leg is allowed to drop off the tables side. Provoked pain in the SIJ region of the lowered leg suggests SIJ dysfunction.[23]

Thigh thrust

The patient is positioned supine. The hip and knee are flexed on one side till the thigh is vertical to the examination table. An arm is wrapped around the flexed thigh and knee and a posteriorly directed force is applied. The opposite hand supports the hip and the SIJ. Pain in the SIJ region is suggestive of SIJ dysfunction.[23]

FABER's (flexion, abduction, and external rotation) test

The patient is positioned supine. The leg is placed in a figure-4 position (hip flexed and abducted with the lateral ankle resting on the contralateral thigh proximal to the knee). While stabilizing the opposite side of the pelvis at the ASIS, an external rotation, abduction and posterior force is then lightly applied to the ipsilateral knee until the end range of motion is achieved. Onset of pain in the SIJ region during this test indicates the likelihood of SIJ dysfunction.[37]

A positive result on the SIJ pain provocation cluster is when three or more positive provocative tests are present. This increases diagnostic accuracy and gives the clinician 35% certainty of having correctly identified SIJ dysfunction according to a recent systematic review and meta-analysis.[35,38] The value of additional imaging diagnostics in SIJ dysfunction is limited, as in the majority of cases no anatomical source can be identified.[39] It can however help to exclude other underlying pathologies, such as hip or spinal pathology. Degenerative changes to the SIJ, such as subchondral bone erosion, subchondral sclerosis, or a vacuum phenomenon, can be identified upon imaging of the SIJ. However, caution must be taken before attributing the complaints to these changes, as these symptoms are also prevalent in many asymptomatic individuals.[24] Computed tomography (CT) scans provide a more detailed anatomy of the bony architecture of the SIJ than fluoroscopy imaging. This makes it a better modality to identify degenerative changes, but it remains an ineffectual tool for identifying SIJ dysfunction, because of low sensitivity and specificity.[40] Magnetic

resonance imaging scans have a high sensitivity in identifying spondylarthritis, such as sacroiliitis, but are not valuable for non-inflammatory conditions.[41]

When additional imaging diagnostics have ruled out other causes of buttock and low back complaints, a diagnostic SIJ intraarticular injection should be performed to confirm SIJ dysfunction.[42,43] This is done by anesthetizing the SIJ with local anesthetic (e.g. lidocaine). The injection is performed under image guidance for increased accuracy. A positive test means that at least a 50% reduction of SIJ pain 30 to 60 minutes following injection occurs. Image guidance modalities in decreasing order of efficacy are CT guided, fluoroscopy guided, and ultrasound guided.[44] Notable pain relief following SIJ intraarticular injection has been shown to provide reliable evidence in the diagnosis of SIJ dysfunction.[15] Nonetheless, discussion remains about the accuracy of SIJ injections to diagnose SIJ dysfunction, mainly due to both false-positive and false-negative results.[45]

Management of SIJ dysfunction

The initial step in the management of SIJ dysfunction is conservative treatment. Similar to that of axial low back pain. Conservative treatment options are always considered first and should focus on the elimination of pain generators and restoring patient function. The use of multiple modalities is advocated. This includes oral analgesics, physical therapy and pelvic belts.[46] Physical therapy modalities are a diverse group of treatments commonly used for musculoskeletal pain. According to a recent review by Al-subahi et al.[47] manual therapeutic techniques appear to be more effective than therapeutic exercises or non-interventional rest in SIJ dysfunction. Manual therapy focusses on direct manipulation and direct mobilization of muscles and joints to produce a therapeutic outcome. A compressive pelvic belt can also be implemented as it has been shown to improve patient reported outcomes.[48] The belt assists in force closure by reducing shear forces across the SIJ in addition to reduce stress across the muscles surrounding the joint. It is also suggested that the use of a pelvic belt is associated with enhanced postural stability.[49] For some patients, the reduction of complaints achieved through conservative treatment options is insufficient.[47] In these cases, intraarticular steroid injections or radiofrequency denervation are other options that can be considered.[23] Intraarticular corticosteroid injections are effective in short-term pain relief, but the overall

effectiveness is limited when it comes to durability.[50] In radiofrequency denervation, thermal energy is used to ablate the sensory nerve fibers of the SIJ, thereby interrupting nociceptive signals.[51] Because of inability to denervate the anterior neural structures to the SIJ and by regeneration of nerves, the effectiveness remains limited.[52–56] Return of complaints within six to twelve months following intraarticular steroid injections or radiofrequency denervation is common, suggesting both are a suboptimal choice for long-term pain relief.[56]

Surgical intervention for SIJ dysfunction should only be considered when pain and functional impairment are refractory to conservative management and other possible pathologies have been ruled out. Open SIJ fusion surgery has been reported in the literature since 1908.[57] Open SIJ fusion is an invasive procedure, in which the surrounding anatomic structures are inevitably prone to damage. Therefore, it is only moderately effective for pain relief and no longer routinely performed for chronic SIJ dysfunction.[58,59] New techniques for SIJ fusion appeared in 1980 using a posterior midline fascial splitting approach in conjunction with screws and plates to facilitate the joint to fuse.[60] In recent years, minimally invasive percutaneous approaches have become the most widely used methods for SIJ fusion.[61,62] Multiple systems for minimally invasive sacroiliac joint fusion (MISJF) are available. One system uses allograft bone plugs to bridge the SIJ and induce arthrodesis.[63] Another uses screw fixation with fenestrated implants covered with osteoconductive coating.[64] Based on the preponderance of literature, most evidence is obtained with cannulated triangular, titanium implants.[65–70] In this technique, it is suggested to place three implants to provide the greatest extent of stability and minimize rotation. Intraoperative fluoroscopy is used for optimal placement. The first implant is mostly seated within the sacral ala. The second implant is generally located above or adjacent to the S1 foramen and the third between the S1 and S2 foramen. Because of anatomical variations, implant location may differ between patients. The ultimate goal of the procedure is to alleviate complaints by eliminating motion. Fusion is anticipated to occur around the three month mark postoperatively, with patients often reporting potential improvements in pain and function earlier in the recovery process.[71] This early relief is believed to be linked to the stabilization of the joint and potential reduction of inflammation. The ultimate therapeutic effect is expected between three to six months after the surgery, as the bones fully fuse and the patient is adapted to the potentially changed biomechanics.[70] Incorporating a personalized physical therapy program is thought to play a crucial role in supporting the potential positive outcomes.[47]

Despite increasing evidence of effectiveness and safety, modern physicians remain critical in selecting patients for MISJF.[72] This skepticism may arise not only from the elusive nature of diagnosing SIJ dysfunction but also from concerns regarding the predominance of industry-funded studies shaping the evidence for MISJF.[73] To date, there is no recognized standard surgical indication for SIJ dysfunction. A general necessity is a positive diagnostic SIJ intraarticular injection (50% reduction of pain). In an industry sponsored study by Polly et al.[74] the latter has been proven to be an excellent predictor for successful MISJF response in terms of reduction of pain and improvement of mobility, also in the long term. In recent years, based on these criteria 120-140 cases of MISJF are performed annually in The Netherlands.

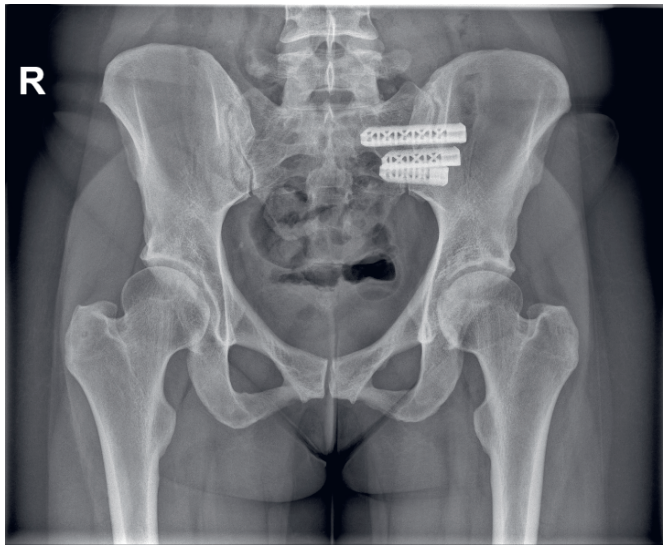


Figure 1.3 Postoperative radiograph of MISJF demonstrating placement of three implants on the left SIJ. *Image used with patient's permission.*

Cost and societal impact

In healthcare economics, costs are divided into two main categories; direct and indirect costs. Direct costs are costs that are directly attributable to patient care, for example in- and outpatient care, surgery, nursing services, medication and diagnostic imaging. Indirect costs are costs that are not directly related to patient

care, for example general productivity losses (absenteeism) and reduced quality of life. For chronic low back pain, the implications on health quality, worker productivity, and social dynamics are marked.[75] Indirect costs compose a significant part of the total costs of back pain.[76] Since SIJ dysfunction is a part of low back pain this also applies to SIJ dysfunction. First, the low quality of life reported by these patients.[19] Second, SIJ dysfunction mainly affects relatively young women, who are in labor force.[70] Third, because diagnosing SIJ dysfunction can be challenging, it is accompanied with diagnostic delay and thus treatment delay.

Current literature on health-economics in SIJ dysfunction is limited. According to an analytic model by Polly et al.[77] including the SIJ in the diagnostic work-up of patients who are considering lumbar fusion surgery could save substantial healthcare costs and avoid unnecessary surgery. Surgery inevitably contributes to a large amount of direct healthcare costs. However, considering the societal impact and the abundance of indirect costs in SIJ dysfunction, MISJF may be cost-saving in the long-term. A cost-effectiveness study by Cher et al.[78] concluded MISJF to be cost-effective after thirteen years versus conservative treatment. However, this industry-funded study is based on an analytic model, and thus has a risk of bias in the analysis and reporting of results. More importantly, consideration of indirect costs is lacking in the analysis. Evidence-based guidelines on the non-surgical and surgical treatment in SIJ dysfunction should be investigated further, with a comprehensive assessment of clinical and economic effects.

Thesis outline

Given the information presented in this introduction, it is clear that there exists a substantial need for further investigation into SIJ dysfunction. Exploring the role of MISJF in this context holds the promise of yielding valuable insights. This thesis is dedicated to examine the potential of MISJF in patients with SIJ dysfunction. Various facets will be explored, encompassing a comparative analysis of MISJF against conservative management, an assessment of its effectiveness in terms of both objective and subjective outcomes, considerations for postoperative care, and an economic evaluation.

To compare the (cost-)effectiveness of conservative treatment and MISJF in SIJ dysfunction, a systematic review and meta-analysis is conducted, which is presented in **chapter two**. In this review, previous literature directly comparing conservative treatment with MISJF was evaluated on clinical and economic outcome. To confirm the findings in the current literature, **chapter three** presents the one-year clinical results of MISJF for SIJ dysfunction in our own industry-independent double center observational study.

To better evaluate the effectiveness of MISJF, not only subjective outcome measures, but also objective outcome measures should be investigated. In **chapter four** a comparative case-controlled study to investigate physical activity in patients with postpartum SIJ dysfunction compared to healthy individuals is presented.

Individuals with chronic low back pain, a common manifestation of SIJ dysfunction, frequently exhibit compromised balance and altered motion patterns resulting from pain-avoidant movements.[79–81] Given the shared symptomatology, investigating if motion pattern alterations exist in SIJ dysfunction is appealing. In **chapters five and six** we concentrate on motion patterns in individuals with postpartum SIJ dysfunction. The initial feasibility study aims to quantify differences between healthy individuals and those with SIJ dysfunction, laying the groundwork for understanding the scope of motion pattern alterations. Subsequently, we investigate the effects of MISJF on motion patterns in the same patients three months following surgery. These studies aim to provide valuable insights into the impact of SIJ dysfunction on postural control, stability and potentially the role of form and force closure principles in these alterations.

Chapter seven is a study protocol for a multicenter randomized controlled trial (RCT) for the effectiveness of MISJF compared to prolonged conservative therapy in SIJ dysfunction: the SACRIFICE study. Current evidence from RCT's on this topic, primarily conducted in the United States, is frequently sponsored by industry. Additionally, many of these studies overlook societal costs. In response, the plan is to undertake a nationwide, industry-independent RCT with a comprehensive assessment of both clinical and economic effects. The overarching goal is to draw indisputable conclusions regarding the effectiveness and economic impact of MISJF compared to conservative management.

In the following chapter of this thesis, the focus is shifted to the aspect of postoperative care following MISJF. Recognizing the significance of optimizing the recovery process, **chapter eight** presents a multicenter RCT. Herein, it is assessed whether intraoperative intraarticular analgesia with bupivacaine 0.50% is superior to placebo (NaCl 0.9%) in reducing postoperative pain, and to determine whether opioid use is reduced in the bupivacaine group during the first 48 hours after surgery.

Lastly, **chapter nine** discusses the main findings of this thesis, the implications of these findings for clinical and scientific practice, and suggestions for future research.

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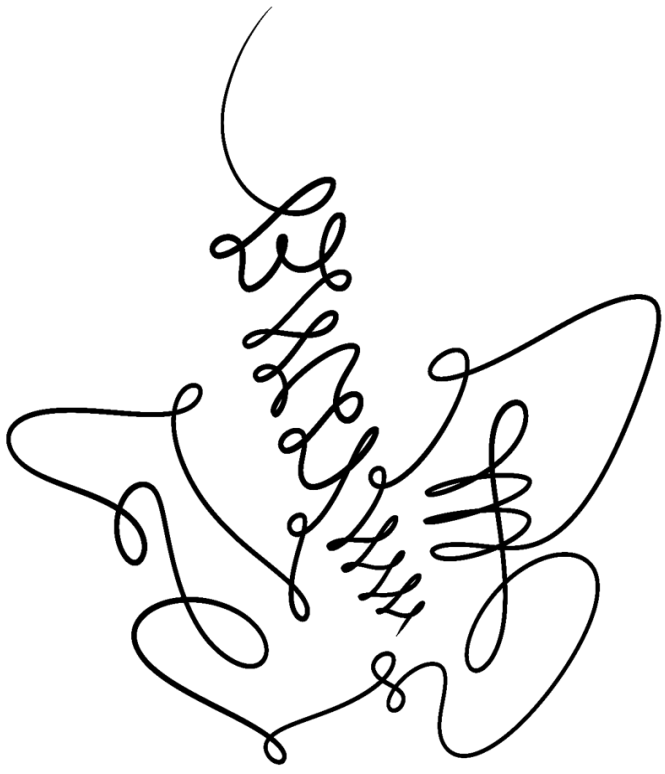

Chapter 2

Minimally invasive sacroiliac joint fusion versus conservative management in patients with sacroiliac joint dysfunction: A systematic review and meta-analysis

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Int J Spine Surg 2022;16(3):472-480

Abstract

Background
The sacroiliac joint (SIJ) is affected in 14% to 22% in individuals presenting with chronic low back or buttock pain. This percentage is even higher in patients who underwent lumbar fusion surgery: 32% to 42%. Currently, there is no standard treatment or surgical indication for SIJ dysfunction. When patients do not respond well to nonsurgical treatment, minimally invasive sacroiliac joint fusion (MISJF) seems to be a reasonable option. This systematic review and meta-analysis evaluates the current literature on the effectiveness of MISJF compared to conservative management in patients with SIJ dysfunction.

Methods
A systematic search of health-care databases was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Inclusion criteria were randomized controlled trials (RCTs) or prospective and retrospective comparative cohort studies that compared MISJF with conservative management. Primary outcome measures were pain, disability, and patient satisfaction measured by patient-reported outcome measures. Secondary outcomes were adverse events (AEs), serious AEs, financial benefits, and costs.

Results
Two RCTs and one retrospective cohort study were included comparing MISJF and conservative management with regard to pain and disability outcome, encompassing 388 patients (207 conservative and 181 surgical). In a pooled mean difference analysis, MISJF demonstrated greater reduction in visual analogue scale-pain score compared to conservative management: –37.03 points (95%CI [–43.91, –30.15], $P<0.001$). Moreover, MISJF was associated with a greater reduction in Oswestry Disability Index outcome: –21.14 points (95% CI [–24.93, –17.35], $P<0.001$). AEs were low among the study groups and comparable across the included studies. One cost-effectiveness analysis was also included and reported that MISJF is more cost-effective than conservative management.

Conclusions
This systematic review and meta-analysis suggest that MISJF, using cannulated triangular, titanium implants, is more effective and cost-effective than conservative management in reducing pain and disability in patients with SIJ dysfunction. Further well-powered, independent research is needed to improve the overall evidence.

Introduction

Low back or buttock pain is a common complaint in the general population. The sacroiliac joint (SIJ) is increasingly being recognized as a potential cause of chronic low back and buttock pain. The SIJ is affected in 14% to 22% in individuals presenting with this pain.[1,2] The frequency of SIJ dysfunction contributing to ongoing back or buttock pain is even more common following lumbar fusion surgery: 32% to 42%.[3] Wide variability exists in the clinical presentation of SIJ dysfunction from localized pain around the SIJ to radiating pain into the groin or even the entire lower extremity.[4] This, sometimes, makes it challenging to accurately diagnose SIJ dysfunction during physical examination. To determine the level and area of tenderness, the SIJ is palpated. There are also several provocative tests described, but their reliability is limited.[5,6] This is most likely because of the limited range of motion of the joint and loading the SIJ will additionally stress surrounding structures.[4] Currently, a positive diagnostic SIJ intra-articular injection is the benchmark for diagnosing SIJ dysfunction.[7,8]

Nonsurgical therapies for SIJ dysfunction, such as oral analgesic use, physical therapy, radiofrequency denervation, and intra-articular steroid injections, are widely propagated. They have shown limited effectiveness when it comes to durability.[9-13] Return of pain 6 to 12 months following intra-articular steroid injections or radiofrequency denervation is common.[13] When patients do not respond well to conservative treatment, surgical intervention is an alternative option. Currently, there is no standard surgical indication for SIJ dysfunction. Open SIJ fusion surgery has been reported in the literature since 1908.[14] Open SIJ fusion is an invasive procedure, in which inevitably the surrounding anatomic structures are prone to damage. Therefore, open SIJ fusion is only moderately effective for pain relief, and no longer routinely performed for chronic SIJ dysfunction.[15,16] New techniques for SIJ fusion appeared in 1980 using a posterior midline fascial splitting approach in conjunction with screws and plates to facilitate the joint to fuse.[17] Minimally invasive sacroiliac joint fusion (MISJF) systems are now available and potentially have better outcomes in relation to pain, disability, and quality of life than the open techniques.[18,19] Multiple techniques and systems for MISJF are available and described in the current literature.

Systematic reviews and/or meta-analyses on MISJF compared to conservative management for SIJ dysfunction in relation to outcome are lacking. The aim of this systematic review and meta-analysis is to evaluate the current literature and

to determine the effectiveness of MISJF compared to conservative management in patients with SIJ dysfunction.

Methods

This systematic review was registered in the PROSPERO database (registration number: CRD42020183360) and conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.[20,21] The research question was formulated as follows:
Is MISJF in adults with low back and/or buttock pain as a result of SIJ dysfunction more effective than conservative management with regard to reduction of pain and disability?

Eligibility Criteria

The review was limited to studies that were published in the English language, and all selected studies had to be published as full-text articles. The last search was run in March 2021.
Inclusion criteria were randomized controlled trials (RCTs) or comparative cohort studies that compared MISJF with conservative management for patients aged 18 years or older. The included studies needed to provide sufficient data relating to all or part of the following outcome criteria: pain, functional outcome, and patient satisfaction measured by patient-reported outcome measures (PROMs).[22-24] Secondary outcomes of adverse events (AEs), serious adverse events (SAEs), and readmission rates were collected if provided. In the MISJF group, the readmission rate was calculated as the number of hospital readmissions after the index surgery divided by the number of index surgeries. Because AEs, SAEs, and readmission rates are interrelated in clinical practice, they were interpreted separately as well as together. Other secondary outcomes were financial benefits and costs.

Search

A systematic search of databases PubMed, CINAHL, Embase, Cochrane, Clinical Trials, World Health Organization, Trial Registry Portal, and PROSPERO was conducted. A detailed search description is included in the appendix; supplementary item 2.1. Relevant clinical studies were selected and reviewed. Full-text articles that met the inclusion criteria, based on their title and abstract, were reviewed for further analysis. Articles identified through the reference list

were considered for data collection based on their title. First 2 independent reviewers (S.H. and R.D.) analyzed the articles by title and abstract. Second, the full-text papers were analyzed independently considering the inclusion criteria. Inter-reviewer disagreements were solved by consensus and with assistance of a third reviewer (I.C.).

Quality Assessment

Quality assessment of the included studies was performed by 2 reviewers (S.H. and R.D) independently.

In case of RCTs, the bias assessment tool of the Cochrane Handbook for Systematic Reviews of Interventions was consulted.[25] Based on six different domains (random sequence generation, allocation concealment, blinding of patients, clinician and outcome assessor, incomplete outcomes data, and selective outcomes data), the included RCTs were evaluated and scored a "low," "high," or "unclear" risk of bias (ROB). The Cochrane Risk of Bias in Nonrandomized Studies of Interventions (ROBINS-I) tool was used to appraise the quality of selected nonrandomized studies.[26] Central features of ROBINS-I include the use of signalling questions to guide ROB judgments within 7 bias domains. These domains were evaluated and scored with "low," "moderate," or "serious" ROB.

Methodological quality of economic evaluations was analyzed using The Consensus Health Economic Criteria (CHEC) list.[27] Levels of evidence were determined using the Oxford Centre for Evidence-based Medicine Levels of Evidence tool (2011).[28]

Statistical Analysis

Statistical analyses of the study data were performed using Review Manager (RevMan v5.3, Cochrane Collaboration, Oxford, UK).[29] Calculations were performed using random effects, fixed effects, mean difference, and a 95% CI. *P* values ≤0.05 were regarded as statistically significant. The I^2-test for heterogeneity was conducted to assess variability between studies. Heterogeneity was regarded as low with an $I^2 \leq 50\%$, moderate with an $50\% < I^2 < 75\%$ and high with an $I^2 \geq 75\%$.

Results

Study Selection

The systematic search (March 2021) in the databases yielded 73 articles, 33 of which remained after removal of duplicates. A total of 6 studies were selected for full-text reading. Two studies were rejected for final analysis because they were subset analyses of other included studies.[30,31] Thus, 4 studies were included in the qualitative synthesis of which 3 studies were included in the quantitative synthesis.[32–34] A PRISMA flowchart detailing the search is shown in Figure 2.1.

Study Characteristics

Two RCTs, 1 retrospective cohort study and 1 cost-effectiveness analysis were included in this review. The total sample size of the RCTs and cohort study consisted of 388 patients of whom 207 were treated conservatively and 181 were treated with MISJF. In all studies, SIJ dysfunction was confirmed with the occurrence of at least 50% pain relief following image-guided intra-articular injection of local anesthetic. In the conservative management group, 63% of patients were women, with a mean age of 49.9 years and a mean body mass index (BMI) of 29.0 kg/m^2. In the MISJF group, 72% were women, with a mean age of 49.2 years and a mean BMI of 28.8 kg/m^2. Publication years ranged from 2016 to 2019. Three studies were conducted in the United States and one in Spain.

The studies from Polly et al.[32] and Dengler et al.[33] were RCTs comparing outcomes after MISIJF vs. conservative management for chronic SIJ dysfunction. Polly et al. allowed crossover from conservative management to MISJF after 6 months. Vanaclocha et al.[34] performed a retrospective comparative cohort study to determine responses to conservative management, including SIJ denervation and MISJF. For PROMS, the visual analogue scale (VAS)-pain and Oswestry Disability Index (ODI) were implemented in the conservative and surgical-treated groups in all 3 studies. Patient satisfaction documented through Short Form (SF)-36 questionnaire was determined in the study by Polly et al. All 3 studies used cannulated triangular, titanium implants with a porous surface for lateral transiliac SIJ fusion (iFuse Implant System, SI-BONE, Inc, San Jose, CA, USA).

The cost-effectiveness analysis performed by Cher et al[35] used quality of life and health-care utilization findings from different ongoing RCTs on MISJF vs. conservative management.[30,31] These data provided estimates of variation in health-care utilization in both MISJF and conservative management. The study implemented a model to determine expected costs and quality-adjusted life years (QALYs) associated with each treatment based on total time spent in different health states (eg, postsurgical mild SIJ pain or postsurgical severe SIJ pain). A relative cost-effectiveness and incremental cost-effectiveness ratio (ICER) were also determined with these data. The studies included in the analysis by Cher et al. used data from the same subsets that were used in the RCTs that were included in this systematic review.[32,33] Patient and study characteristics of the included literature are outline in Table 2.1.

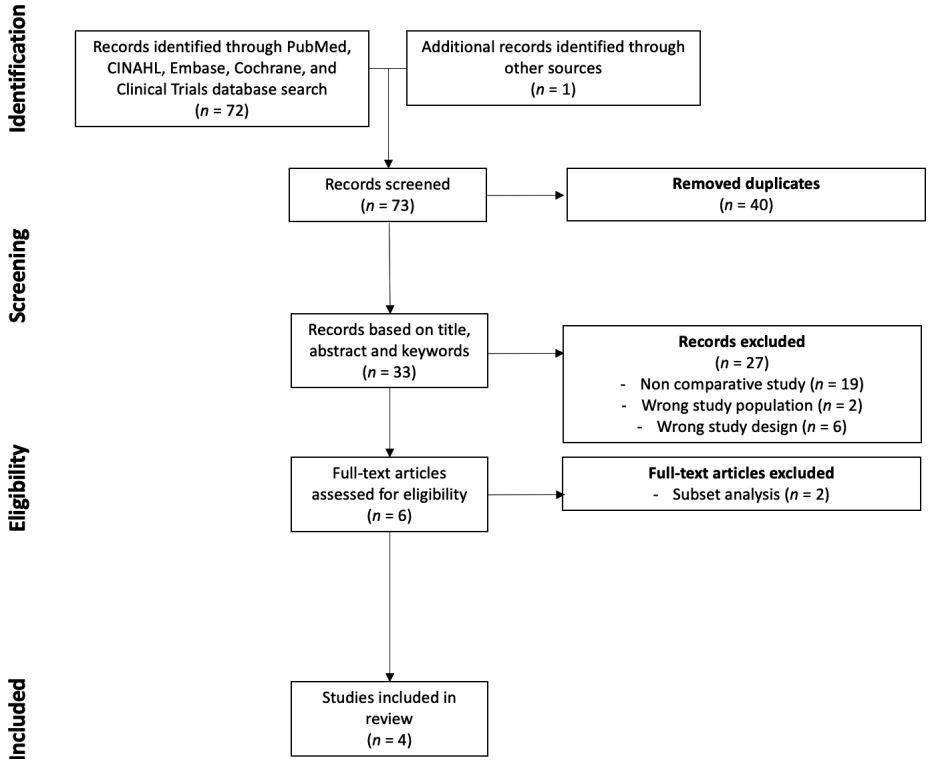

Figure 2.1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowchart.

Table 2.1 Study characteristics.

		Minimally Invasive Sacroiliac Joint Fusion Group		Conservative Management Group			Quality Assessment	
Study	**Study Design**	**Participants, *n* (% Women)**	**Age, y, mean (Range)**	**Participants, *n* (% Women)**	**Age, y, mean (Range)**	**Follow-Up (mo)**	**Level of Evidence**	**Overall risk of bias**
Polly et al. 2016	Randomized controlled trial	102 (73.5%)	50.2 (25.6 to 71.7)	46 (60.9%)	53.8 (29.5 to 71.1)	24	1	Low
Dengler et al. 2019	Randomized controlled trial	52 (73.1%)	49.4 (27 to 70)	51 (72.5%)	46.7 (23 to 69)	24	1	Low
Vanaclocha et al. 2017	Retrospective comparative cohort	27 (70.4%)	48.0 (25 to 69)	110 (55.2%)	49.7 (24 to 70)	72	4	Moderate
Cher et al. 2016	Cost-effectiveness analysis	274	–	46	–	12	–	–

Quality Assessment

The ROB was evaluated for the included studies. The RCTs from Dengler et al.[33] and Polly et al.[32] scored an overall low ROB. Only risk of performance bias was high in both studies because patients or investigators were blinded. Vanaclocha et al.[34] scored an overall moderate ROB, which was expected because of its retrospective nature. Noteworthy, the studies by Dengler et al., Polly et al., and Cher et al. were funded by SI-BONE, the manufacturer of the iFuse implant system. Industry funding is not implemented in the bias assessment tool of Cochrane.

Quality of the included cost-effectiveness analysis by Cher et al.[35] was high according to the CHEC-list. With a score of 17 out of 19, only "generalization" and "ethical issues" were domains insufficiently discussed in the paper. A full elaboration of the methodological quality assessment is included as included as supplementary item 2.2 and 2.3 in the appendix.

Results of studies

Tables 2.2 and 2.3 summarize the results of the included studies with regard to VAS-pain and ODI. Polly et al.,[32] Dengler et al.,[33] and Vanaclocha et al.[34] compared VAS-pain outcome in patients who underwent MISJF compared with patients who were treated conservatively. All 3 found a statistically significant difference in favor of the MISJF groups, respectively, 38.2 and 34.0 points on a 0 to 100 scale and 6.0 points on a 0 to 10 scale. Similarly, statistically significant ODI differences were reported in favor of the MISJF groups, respectively, 23.8, 18.0, and 24.0 points. Only Polly et al. reported on changes in SF-36. A statistically significant improvement in SF-36 was noted within the MISJF group at 6, 12, and 24 months, respectively, 12.5, 12.8, and 11.2 points. While the mean SF-36 score of the conservative management group at 6 months remained low at 3.9 points. This difference between treatment groups was statistically significant. The crossover rate in Polly et al. from conservative management to MISJF at 6 months was 89%.

Table 2.2 Study results for mean (SD) VAS-pain score.

	VAS-Pain MISJF Group, mean (SD)			VAS CM Group, mean (SD)		
Study	Preop	Postop (6 mo)	Postop (24 mo)	Preop	Postop (6 mo)	VAS-Pain Improvement Comparison Between Groups[a]
Polly et al. 2016	82.3 (11.9)	30.1 (29.4)	26.5 (29.8)	82.2 (9.9)	70.3 (25.9)	38.2 (P<0.0001)
Dengler et al. 2019	77.7 (11.3)	34.4 (23.9)	31.8 (29.8)	73.0 (13.8)	67.8 (20.3)	34 (P<0.0001)
Vanaclocha et al. 2017	7.8 (1.4)	2.4 (1.1)	1.6 (0.8)	7.5 (1.4)	7.2 (1.8)	6 (P<0.001)

Abbreviations: CM; conservative management,MISJF, minimally invasive sacroiliac joint fusion; Postop, postoperative; Preop, preoperative; VAS-pain; visual analog scale for pain. [a]VAS-pain improvement in the MISJF group compared to the CM group (combining timepoints).

Table 2.3 Study results for mean (SD) ODI.

	ODI MISJF Group, mean (SD)			ODI CM Group, mean (SD)		
Study	Preop	Postop (6 mo)	Postop (24 mo)	Preop	Postop (6 mo)	ODI Improvement Comparison Between Groups
Polly et al. 2016	57.2 (12.8)	29.9 (20.5)	28.5 (21.9)	56.0 (14.0)	51.6 (18.8)	23.8 (P<0.0001)
Dengler et al. 2019	57.5 (14.4)	32.0 (18.4)	30.2 (19.0)	55.6 (13.7)	50.2 (17.2)	18 (P<0.0001)
Vanaclocha et al. 2017	41.7 (6.8)	25.2 (5.7)	18.4 (5.3)	38.3 (7.9)	38.9 (8.3)	24 (P<0.001)

Abbreviations: CM; conservative management,MISJF, minimally invasive sacroiliac joint fusion; ODI; Oswestry Disability Index; Postop, postoperative; Preop, preoperative. [a]ODI improvement in the MISJF group compared to the CM group (combining timepoints).

Adverse Events

All studies reported on AEs/SAEs. A total of 81 AEs/SAEs occurred in a total study population of 341 patients. Fifty AEs/SAEs occurred in the MISJF study groups, and 31 AEs occurred in the conservative management groups. Furthermore, 17 failures in treatment were mentioned, 11 in the MISJF groups, and 6 in the conservative management groups. No statistically significant differences were reported regarding the rate of AEs across MISJF groups and conservative management groups. Failure to treatment was regarded as recurrent SIJ pain after surgery or persistent or increased pain after conservative management.

Of the 50 AEs related to MISJF, 10 were regarded as SAEs, including surgical wound problems (*n*=5) and implant malposition (*n*=5). Implant malposition caused persistent radicular pain because of nerve root impingement in 2 patients and persistent SIJ pain in 1 patient. All 3 required readmission with revision surgery, repositioning the implant. Revision surgery was effective in all 3 cases. Recurrent SIJ pain after surgery occurred in 11 patients and was considered as failure to treatment. Other AEs reported in the studies included trochanteric bursitis, urinary retention, nausea/vomiting and atrial fibrillation.

Of the 31 AEs related to conservative management, 0 were rated as serious. The following AEs were probably related to conservative management: new pain in the pelvic area (*n*=5), new low back pain (*n*=4), SIJ pain due to physiotherapy (*n*=1), back pain due to physiotherapy (*n*=1), SIJ pain related to a steroid injection (*n*=1), and flushing and shortness of breath related to a SIJ steroid injection (*n*=1). Failure to treatment occurred in 6 patients: persistent SIJ pain (*n*=1) and worsening of SIJ pain (*n*=5). Other AEs reported in the studies included hypertensive crisis, herpes infection, depression, carpal tunnel syndrome, stress incontinence, menometrorrhagia, medication overdose, cervicobrachialgia, worsening ulcerative colitis, and brain metastases.

Cost-Effectiveness

The cost-effectiveness analysis performed by Cher et al.[35] reported that MISJF was associated with an average 5-year total cost per patient of US $22,468 (95% CI $17,215–$27,888). The average 5-year total cost of conservative management in SIJ dysfunction was US $12,615 (95% CI $10,336–$15,065). The incremental cost of MISJF relative to conservative management was $9833 with an incremental QALY gain of 0.74 per year at a corresponding ICER of $13,313 per QALY gained.

Meta-Analysis

Data reported by Polly et al.,[32] Dengler et al.[33], and Vanaclocha et al.[34] were used to perform a meta-analysis. For the meta-analysis of VAS-pain, only data from Polly et al. and Dengler et al. were analyzed, as Vanaclocha et al. reported VAS-pain on a 0 to 10 scale while Polly et al. and Dengler et al. used a 0 to 100 scale. Baseline scores for VAS-pain and ODI across MISJF and conservative management groups were similar. An outcome timepoint of 6 months for both study groups was implemented. Study heterogeneity was low for VAS-pain and ODI with an I_2 of 0% for both fixed and random effects analysis. The overall effect for VAS-pain outcome was in favor of the MISJF group with a statistically significant mean difference of –37.03 points (95% CI [–43.91, -30.15], P<0.001). The overall effect for ODI outcome was also in favor of the MISJF group with a statistically significant mean difference of –21.14 points (95% CI [–24.93, –17.35], P<0.001). Forest plots are included as Figures 2.2 and 2.3 in the figure legend.

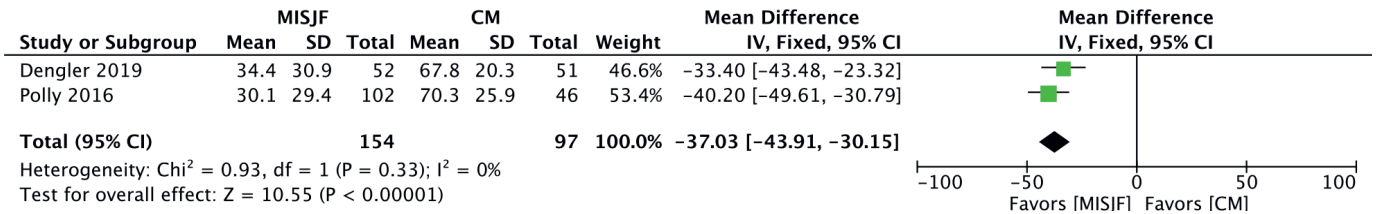

Figure 2.2 Comparison between MISJF and CM for the outcome of VAS-pain after 6 mo; CI, confidence interval; CM, conservative management; MISJF, minimally invasive sacroiliac joint fusion; VAS, visual analog scale.

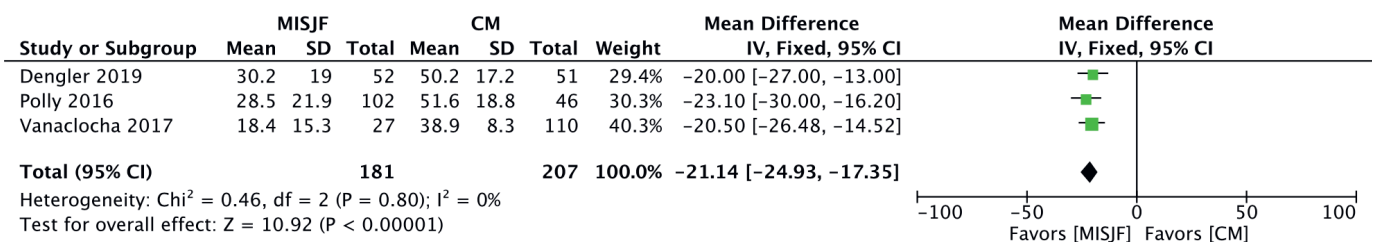

Figure 2.3 Comparison between MISJF and CM for the outcome of ODI after 6 mo; CI, confidence interval; CM, conservative management; MISJF, minimally invasive sacroiliac joint fusion; ODI, Oswestry Disability Index.

Discussion

The most important findings of the present systematic review and meta-analysis are that MISJF, using lateral transiliac approach with cannulated triangular, titanium implants, suggests to be more effective in reducing pain and disability in patients with SIJ dysfunction compared to conservative management. Also, MISJF suggests to be cost-effective when compared to the current conservative treatment options. The included studies reported statistically significant differences in clinical outcome in favor of the MISJF groups.[32–34] The decrease reported in the included studies of VAS-pain and ODI after MISJF is clinically relevant, as the VAS-pain reduction is 50.9 points and the decrease in ODI is 26.4 points.[36,37] There were no statistically significant or clinically relevant improvements of VAS-pain and ODI in conservatively treated patients. Furthermore, the crossover rate of 89% in Polly et al. from conservative management to MISJF also indicates high ineffectiveness of conservative management. Quantitative analysis for VAS-pain and ODI outcomes across included studies revealed a homogeneous trend with an I^2 of 0% across analyses (Figures 2.2 and 2.3).[32–34] This trend is also demonstrated in the qualitative analysis of this paper. Whang et al.[31] was excluded in the quantitative analysis of VAS-pain, as it reported VAS-pain on a 0 to 10 scale, introducing statistical heterogeneity.

The studies by Polly et al.[32] and Dengler et al.[33] had a follow-up of 24 months for the MISJF groups and 6 months for the conservative management groups, with the notion that no further improvement in terms of pain and disability is to be expected after 6 months of conservative management.[38] Vanaclocha et al.[34] had a follow-up of up to 72 months for both MISJF and conservative treated patients. The MISJF groups across included studies continued to show significant improvements in VAS-pain and ODI scores up to 24 months and even 72 months after surgery. These data suggest that the positive effects from MISJF are still present in the long term.

Meta-analysis was not implemented to summarize AEs/SAEs across included studies, as the methods to collect these events were not detailed. The rate of AEs reported in the surgical and conservative management groups was low and consistent among the included studies with no significant differences between groups. SAEs were uncommon and occurred in 5 surgical patients, all being implant malpositioning. A possible explanation for this phenomenon is that correct placement of the implants across the SIJ is a difficult procedure with a long learning curve.[39] Nonetheless, the overall positive outcomes of MISJF seem

to outweigh the potential SAEs. These findings are supported by 2 previously performed safety analyses.[40,41]

With an incremental cost of $9833 for MISJF compared to conservative management and an addition of 0.74 QALY, Cher et al.[35] concluded that MISJF is a cost-effective, and, in the long run, a cost-saving approach for SIJ dysfunction. The cost-effectiveness is comparable to that of total hip and knee arthroplasty. A recent administrative claims analysis reported lower postoperative low back pain-related health-care costs compared to preoperative costs for MISJF.[42] The study was not included in this systematic review, as it did not compare MISJF with conservative management. These findings also support the financial benefits of MISJF for patients with chronic SIJ dysfunction.

In current systematic reviews that solely evaluate the effectiveness of MISJF in patients suffering from SIJ dysfunction, different implant systems are described and clustered.[43,44] When all data are pooled, a statistically significant reduction in VAS-pain can be observed. However, the effectiveness of different implant systems varies across the current literature. Multiple trials investigated the efficacy of cannulated triangular, titanium implants, with clinically significant differences in pain and disability.[45–50] For other systems, such as titanium cages and hollow modular screws, significantly less evidence in the literature is available.[51] The evidence supporting the latter systems comes mostly from small prospective or retrospective case series; therefore, these studies are of lesser methodological quality.[52–55]

As mentioned before, several studies describe significant improvements in clinical outcome following MISJF.[45–50] Most of these studies did not meet our inclusion criteria as they did not compare the outcomes to a conservative management group. Statistically significant improvements in VAS-pain and ODI are reported in these studies with a mean follow-up of 20 months. Although the differences in pre- and postoperative VAS-pain and ODI are clinically relevant, it is reported that in some patients not all pain and disability resolved after surgery. Across studies, 77.1% to 93.8% of patients were satisfied after surgery and 88.4% to 91.7% of patients would have the same surgery again.[45–49] These results suggest that a small number of patients do not respond adequately to surgery or expected more improvement in pain and disability. It can be postulated that wrong indications or other patient-related factors, such as patient expectations, are of influence on the outcome, which is commonly encountered in other surgical procedures.[56]

Limitations

This systematic review and meta-analysis are bound by several important limitations in the available literature. Exploration of the literature indicated a limited availability of studies that met the strict inclusion criteria. Furthermore, only 1 SIJ fusion technique was implemented in the included studies, a lateral transiliac approach with cannulated triangular, titanium implants. Research on MISJF is performed by only a few research departments across the world, as a result many overlapping cohorts are published in the current literature.[30,31] Although the sample sizes are generally small, we were able to perform a meta-analysis with the included data. According to Greco et al.,[57] performing a meta-analysis with a small number of studies can still provide useful insights. Because of homogeneity in reported results in included studies, we chose to compute the pooled estimates of differences between MISJF and conservative management, resulting in an $I2$ of 0% across all analyses. For the meta-analysis of VAS-pain only data from Polly et al.[32] and Dengler et al.[33] were analyzed, as Vanaclocha et al.[34] reported VAS-pain on a different scale. Although most of the outcome measurements are validated tools, they remain PROMs and are thereby at risk for some sort of subjective discrepancies. A validated objective outcome measurement in SIJ dysfunction for diagnostic, as well as evaluative purposes, is currently lacking.

In the study by Vanaclocha et al., all patients were initially treated conservatively. When conservative treatment failed, patients with a positive response to SIJ intra-articular injection were enrolled in prolonged conservative management or MISJF. In the studies by Polly et al. and Dengler et al., it remains unclear whether patients already underwent conservative treatment before enrolling in the randomized trial.

Finally, even though the ROB of the included studies was low to moderate, 3 out of the 4 included studies were funded by SI-BONE, the manufacturer of the iFuse implant system, potentially introducing bias into the reporting of results.

As a result of these limitations, the outcomes of this review and meta-analysis should be interpreted with some caution.

Conclusions

This article is the first systematic review and meta-analysis to evaluate the effectiveness of MISJF, using cannulated triangular, titanium implants, compared with conservative management for SIJ dysfunction. Although the

level of evidence is limited, mostly due to small sample sizes, based on the assessment of the included studies, MISJF suggests to be more (cost-)effective in reducing pain and disability in patients with SIJ dysfunction compared to conservative management. More data are required from well-powered, independent, RCTs with validated outcome measurements to make undisputed conclusions about the efficacy and financial benefits of various MISJF implants compared to conservative management. This review could function as a base for these particular trials.

Acknowledgment

The authors would like to thank Prof. Dr. Vanaclocha from the University of Valencia and Dr. Cher and Dr. Polly from SI-BONE, California, for providing us with essential data to include a meta-analysis in this article, improving the scientific evidence.

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Appendix 2.1

Supplementary item 2.1: Search terms

(((((((sacroiliac joint* pain [tiab]) OR sacroiliac joint* dysfunction [tiab]) OR sacroiliac dysfunction [tiab]) OR "Sacroiliac Joint"[Mesh]) OR sacroiliac joint* [tiab])) AND ((((((((Sacroiliac joint* fusion [tiab]) OR minimally invasive sacroiliac joint* fusion* [tiab]) OR sacroiliac joint* arthrodesis [tiab]) OR minimally invasive sacroiliac joint* arthrodesis [tiab]) OR Sacroiliac fusion* [tiab]) OR triangular titanium implants [tiab])))) AND ((((((("Conservative Treatment"[Mesh]) OR Conservative treatment [tiab]) OR conservative management [tiab]) OR non-surgical treatment [tiab]) OR non-surgical management [tiab]) OR sacroiliac radiofrequency denervation [tiab]) OR sacroiliac injection* [tiab]) OR sacroiliac intraarticular steroid injection* [tiab])) AND ((((((((((((VAS [tiab]) OR VAS score [tiab]) OR Oswestry Disability Index [tiab]) OR SF-36 [tiab]) OR EQ-5D [tiab]) OR surgical outcome [tiab]) OR non-surgical outcome [tiab]) OR pain score [tiab]) OR patient satisfaction [tiab]) OR QALY [tiab]) OR costs [tiab]) OR adverse event* [tiab]) OR readmission* [tiab])

Supplementary item 2.2: Risk of bias tables

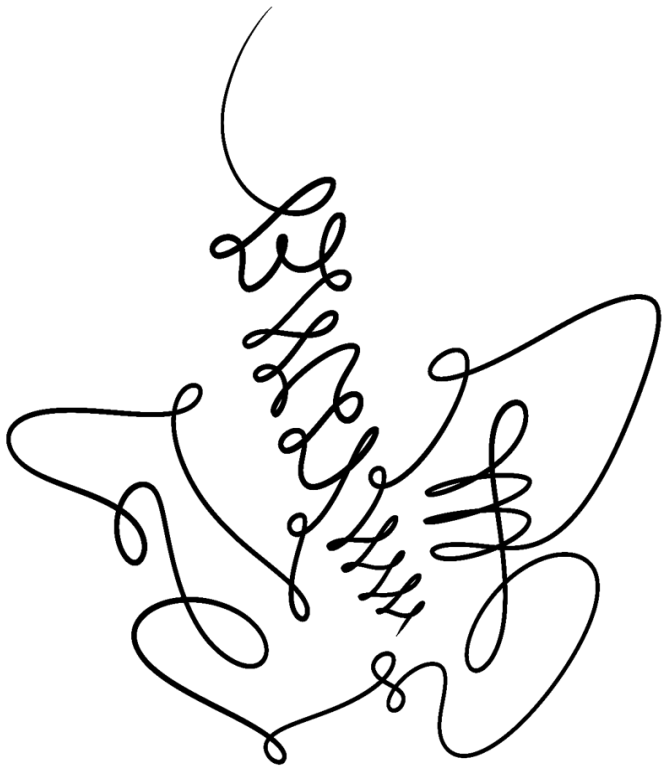
Study	Study design	Bias due to confouding	Bias in selecting patients	Bias in classification of interventions	Bias due to deviation from intended intervention	Bias due to missing data	Bias in measure outcome	Bias in selection of the reported results	Other	Conclusion
Vanaclocha et al. 2017	Retrospective comparative case series	Low	Low	Low	Low	Moderate	Moderate	Moderate	Unclear	Moderate

Study	Study design	Selection bias	Performance bias	Detection bias	Attrition bias	Reporting bias	Other bias	Conclusion
Polly et al. 2016	Randomized controlled trial	Low	High	Unclear	Low	Low	Unclear	Low
Dengler et al. 2019	Randomized controlled trial	Low	High	Low	Low	Low	Low	Low

Author/year	Study design	Risk of bias
Vanaclocha et al. 2017	Retrospective comparative case series	• Bias due to confounding: Low *Confounder analysis is accounted for* • Bias of selecting patients: Low *The indications and in- and exclusion criteria are clearly stated* • Bias in classification of interventions: Low *The classification between groups is clear.* • Bias due to deviation from intended intervention: Low *There was no crossover.* • Bias due to missing data: Moderate *Lost-to-follow-up is mentioned briefly.* • Bias in measure outcome: Moderate *PROM's were used as primary outcome* • Bias in selection of the reported result: Moderate *Significance is not mentioned, although P-values are available in table.* • Other bias: Unclear • **Overall: MODERATE**
Dengler et al. 2019	Randomized controlled trial	• Selection Bias: Low *1:1 Web-based Randomization using block stratification* • Performance Bias: High *Patients nor investigators were blinded.* • Detection Bias: Low (PROMs& blinded radiologist) • Attrition Bias: Low *Withdrawals explained. Missing data is mentioned and not imputated.* • Reporting Bias: Low *Not significant differences are reported* • Other Bias: Low *Conflict of interest is accounted for.* • **Overall: LOW**
Polly et al. 2016	Randomized controlled trial	• Selection Bias: Low *1:2 Web-based randomisation using block stratification* • Performance Bias: High *Patients not blinded, surgeon not mentioned* • Detection Bias: Unclear *Blinding during assessment not mentioned.* • Attrition Bias: Low *Both withdrawals and missing data are mentioned and explained* • Reporting Bias: Low *Not significant differences are reported* • Other Bias: Unclear *Conflict of interest is mentioned and briefly described, but no further information is given.* • **Overall: LOW**

Supplementary item 2.3: Consensus Health Economic Criteria (CHEC) list

	1. Describes study population	2. Competing alternatives	3. Research question	4. Economic study design	5. Time horizon	6. Perspective	7. Relevant costs	8. Appropriately measured	9. Appropriately valued costs	10. Relevant outcomes	11.Appropriately	12. Appropriately valued	13. ICER	14. discounted	15. Sensitivity analyses	16. correct conclusions	17. generalization	18. conflict of interest	19. ethical issues	Total +
Cher et al.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	17



Chapter 3

Double-center observational study of minimally invasive sacroiliac joint fusion for sacroiliac joint dysfunction: One-year results

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J Orthop Surg Res 2022;17(1):570

Abstract

Background
A substantial part of patients with chronic low back pain, the origin is located in the sacroiliac joint (SIJ). Minimally invasive sacroiliac joint fusion (MISJF) is increasingly being implemented as a treatment option in SIJ dysfunction. Despite remaining controversy, evidence continues to increase. This study evaluates the clinical results and safety of MISJF in a double-center consecutive case series in patients with SIJ dysfunction over a one-year observation period.

Methods
SIJ complaints were diagnosed after history taking, physical examination and least a 50% reduction of SIJ pain 30 to 60 minutes following image-guided injection. Primary outcome measures were patient reported outcome measurements (PROMs), consisting of Visual Analogue Scale (VAS) pain score and EuroQol 5-dimensions 3-levels (EQ-5D-3L). Patients' perspectives on the effects of surgery were collected through questionnaires. Secondary outcome measures were implant positioning and (serious) adverse events ((S)AE's).

Results
A total of 29 patients were included. In 44.8% of patients SIJ dysfunction was of postpartum origin. The mean VAS-pain score improved from 7.83 (±1.71) to 4.97 (±2.63) postoperatively ($p<0.001$). EQ-5D-3L score improved from 0.266 (±0.129) to 0.499 (±0.260) postoperatively ($p<0.001$). Opioid consumption decreased from 44.8% to 24.1% postoperatively ($p=0.026$). In 13.7% of patients an (S)AE occurred.

Conclusion
MISJF appears to be an effective and safe procedure in this cohort. Statistically significant and clinically relevant improvements in pain and quality of life were observed one-year postoperatively. Future studies should focus on the long-term outcomes to further evaluate the safety and effectiveness of MISJF.

Introduction

Chronic low back pain is a common health problem worldwide, and one of the major causes of disability.[1] Sacroiliac joint (SIJ) dysfunction is an often overlooked cause of complaints. In 14-22% of patients with chronic low back pain the origin is located in the SIJ.[2–4] The etiology of SIJ dysfunction varies, most cases include posttraumatic degenerative or postpartum origins.[5] Prior lumbar fusion surgery and connective tissue disorders are also a prevalent risk factor for development of SIJ dysfunction.[6,7] Despite the available conservative treatment options, many patients continue to have a considerable reduced quality of life (QoL) due to persistent SIJ pain.[3] The impaired QoL for patients with SIJ dysfunction is comparable to other orthopedic conditions with an indication for surgery.[8] Surgical treatment options for SIJ dysfunction have been unattractive for a long period of time. Mainly because open arthrodesis of the SIJ is associated with high morbidity and only moderate long-term results.[9–11] Currently, several minimally invasive sacroiliac joint fusion (MISJF) systems are available for fusion of the SIJ. Most evidence is obtained with cannulated triangular, titanium implants based on the preponderance of literature.[12–17] The initial outcomes of these procedures are promising in terms of pain reduction and improvement of mobility.[18] Despite increasing evidence of effectiveness, controversy remains on the role of interventional procedures, potentially because diagnosing SIJ dysfunction can be elusive or previous open surgery for SIJ pain was not appealing. To this day, there is no recognized standard surgical indication for SIJ dysfunction and often a prolonged conservative trajectory is followed.[5] Most of the current studies on MISJF are industry funded, hence having a potential risk of bias in the reporting of results.
Presently, only a few centers in The Netherlands have introduced MISJF for patients with chronic SIJ dysfunction. This independent study aims to evaluate the results and safety of MISJF in a double-center consecutive case series in patients with SIJ dysfunction over a one-year observation period.

Material and methods

Study design

This study was a retrospective study of consecutive series of patients that received MISJF, between 15 April 2019 and 19 June 2020, in two specialized SIJ dysfunction centers in The Netherlands (Zuyderland Medical Center, Heerlen

and Medical Spectrum Twente, Enschede). Patients were selected by chart review, as all patients that underwent MISJF were analyzed. The study outcomes were questionnaire based, with surveys being taken preoperative and one-year postoperative. Preoperative data was collected at the outpatient clinic and postoperative follow-up data was retrieved by contacting patients through mail. Preoperative imaging diagnostics included X-rays and optional computed tomography (CT) scans of the pelvis. A corresponding CT scan was scheduled to be obtained one day following surgery.

Population

Patients were strictly selected for MISJF based on the following criteria. Prior to surgery, all patients were examined by one of three specialized MISJF surgeons (WvH, IC, JN). Besides medical interviewing, the examination included the following SIJ provocative tests; flexion abduction external rotation (FABER-test), thigh thrust, Gaenslen's test, sacral distraction, lateral compression, and sacral thrust.[19] When at least 3 provocative tests evoked SIJ pain, patients received an image-guided intra-articular SIJ injection with local anesthetic according to a specific guideline.[20] The injections were performed by a specialized MISJF surgeon or experienced pain specialist. Final diagnosis of SIJ dysfunction was based on physical examination and at least a 50% reduction of SIJ pain 30 to 60 minutes following fluoroscopy-guided injection with lidocaine 2%. Contrast was used to ensure proper needle placement. Other causes of low back pain were excluded through physical examination and additional imaging, for instance with spine and/or pelvic radiographs or even through magnetic resonance imaging. All patients had received an extensive conservative treatment trajectory of at least one year, including physical therapy, pelvic compression belt and SIJ infiltration.
Adult patients who eventually received unilateral or staged bilateral MISJF for SIJ dysfunction were eligible for inclusion. Patients were included when preoperative patient reported outcome measurements (PROMs) and follow-up data, defined as at least one outpatient follow-up visit, were collected and documented in electronic patient records.

Surgery

All patients were treated with MISJF using a series of triangular titanium, porous titanium plasma spray coated implants (iFuse Implant System®; SI-BONE, Inc., San Jose, CA, USA). After administration of general anesthesia, the

patient was placed in prone position. During MISJF, intraoperative fluoroscopy was used for optimal placement of implants. Lateral view and pelvic inlet and outlet views were utilized to obtain an appropriate starting point. A 3cm lateral incision was made across the sacral midline. Under lateral fluoroscopy view the first guide pin was positioned at the appropriate starting point. In- and outlet view were used to place the guide across the ilium and across the SIJ until correct depth was reached. Length of the implant was measured. Subsequently a drill followed by a triangular broach were used to decorticate the bone and prepare the pathway to receive the first implant. This implant was mostly seated within the sacral ala. Same procedure was repeated for the second and third implant. The second implant was generally located above or adjacent to the S1 foramen and the third between the S1 and S2 foramen. The position and number of implants differed between cases. The incision was then irrigated with bupivacaine and the tissue layers are sequentially closed.

Data collection

Data were collected through chart review and stored in a coded and secured database. Besides PROMs, baseline characteristics were collected, which included: sex, age, Body Mass Index (BMI), American Society of Anesthesiologists (ASA) classification, pre- and postoperative use of opioid medication, medical history, medical imaging, surgical technique, (serious) adverse events ((S)AE)) and PROMs.

Follow-up outcomes

The primary outcome measures were PROMs, including Visual Analogue Scale (VAS) pain score (0-10, 10 being 'worst pain imaginable') and EuroQol 5 dimensions 3 levels (EQ-5D-3L, 0.01 to 1.00, 1.00 indicates 'best health state') and the EQ self-reported health status that records the respondent's self-rated health (0-100, 100 being 'best imaginable health state'). The EQ-5D-3L value was set on "Europe". Further details on patient's perspective on the effects of the procedure were evaluated using statements. Possible responses range from strongly agree to strongly disagree, according to the Likert principle.[21] All statements are outlined in the appendix as supplementary item 3.1. The postoperative PROMs questionnaires were mailed to the participants and completed by the patients independently. Secondary outcome measures were opioid consumption, implant positioning on postoperative CT, and (S)AE's. Musculoskeletal radiologists familiar with MISJF evaluated all CT scans. This

evaluation included the position of the implants and the ossification between the sacrum and the ilium on later CT scans. All (S)AE's, including causes of re-hospitalization, surgical related events, and reoperations for MISJF were analyzed as well.

Statistical analysis

Statistical analyses were carried out using IBM SPSS statistics 27 (Inc., Chicago, IL). All descriptive data are presented as means with standard deviations (SD), frequencies (%) or medians with ranges. Descriptive data were generated for all variables. Univariate analysis was performed for baseline characteristics. Data was tested for normal distribution. When data was normally distributed a paired t-test was used to determine statistical difference between pre- and postoperative data. In case of absence for normal distribution Wilcoxon Signed-Rank test was used. Categorical data was assessed using Chi-Square and Fisher's exact test. A p-value ≤0.05 was considered statistically significant. EQ-5D-3L index scores were calculated through a European value set.[22]

Ethics, registration, data sharing plan, funding, and potential conflicts of interest

This study has been approved by the Medical Ethical Committee (METCZ20200224) at both participating centers. This study was registered in the Netherlands trial register (registration number: NL9351) and was written in accordance with the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) guidelines.[9]

Results

Baseline characteristics

The medical charts of 57 patients that underwent primary MISJF were reviewed, of whom 29 patients were included. In these 29 patients pre- and postoperative data were available. Baseline characteristics are presented in Table 3.1. The majority of patients in this cohort were women (86.2%) with a mean age of 45.6 years. In most cases the cause of SIJ dysfunction was of postpartum origin (44.8%), followed by Ehlers Danlos Syndrome (EDS) (13.8%). In the first year of follow-up, six (20.7%) patients underwent a staged bilateral procedure. In 7 patients (24.1%) degenerative changes to the SIJ were observed (e.g., vacuum

phenomena or sclerosis of the endplates) on preoperative imaging. There were no patients with sacral dysmorphism in this cohort. Almost all patients received three implants over the SIJ during surgery (93.1%). The average procedure duration was 47.8 minutes (± 14.7). Further characteristics regarding the index procedure are outlined in Table 3.2.

Table 3.1 Baseline characteristics.

Characteristics	**Value**
Age, years	45.6 (± 8.6)
Women	25 (86.2%)
BMI, kg/m^2	27.1 (± 4.4)
ASA	
I	5 (17.2%)
II	22 (75.9%)
III	2 (6.9%)
Preoperative opioid consumption	13 (44.8%)
Medical history	
Prior spinal fusion	3 (10.3%)
Prior MISJF (other side)	4 (13.8%)
Other spine surgery	3 (10.3%)
Preoperative imaging abnormality	
None	13 (44.8%)
Degenerative SIJ	7 (24.1%)
Other	9 (30.9%)
Cause of SIJ dysfunction	
Postpartum	13 (44.8%)
Prior spinal fusion	3 (10.3%)
Ehlers-Danlos syndrome	4 (13.8%)
Posttraumatic	2 (6.9%)
Degenerative	2 (6.9%)
Unknown	5 (17.2%)

Data are presented as frequency (n, %) or mean (range).

Table 3.2 Index procedure characteristics.

Characteristics	Value
Side, right	16 (55.2%)
Amounts of implants placed	
2	2 (6.9%)
3	24 (93.1%)
Procedure duration, minutes	47.8 (± 14.7)
Adverse events	
Intraoperative	1 (3.4%)
Postoperative	3 (10.3%)
Loosening of implants	2 (6.8%)
Wound infection	1 (3.4%)

Data are presented as frequency (n, %) or mean (range).

Primary outcome measures

A statistically significant reduction in pain occurred at one-year following surgery compared to baseline (p<0.001). Mean VAS-pain score improved from 7.83 (± 1.71) pre- to 4.97 (± 2.63) at one-year postoperative with a mean change of 2.86 (± 2.94) points. In nine patients (30.9%) a VAS-pain score of 3 or lower was reported. QoL measured through EQ-5D-3L revealed a statistically significant mean improvement of 0.232 (± 0.243) points (p < 0.001). The VAS on self-reported health status also improved with statistical significance by 11.7 (± 28.3) points following surgery (p=0.035). Complete data regarding VAS-pain and EQ-5D-3L outcomes are outlined in Table 3.3.

Twenty-three patients (79.3%) "agree" or "totally agree" on the statement whether their complaints reduced following surgery. Eight patients (27.5%) "agree" or "totally agree" to be completely free of complaints after treatment. When looking at improved health or QoL we observe an almost similar response. Health improved in 16 patients (55.2%) following treatment and 17 patients (58.6%) "agree" or "totally agree" that their QoL improved. When asked if patients would have the same surgery for the same result again, 24 patients (82.8%) "agree" or "totally agree". Twenty-five patients would recommend the same surgery to individuals with similar complaints (86.2%). Finally, 18 patients (62.1%) are satisfied with the results of the procedure. Results of the statements regarding patient's perspective on effects of the procedure are displayed in figure 1.

Table 3.3 Results.

Outcome	Preoperative	1 year postoperative	Mean difference	p-value
Pain, VAS	7.83 ± 1.71	4.97 ± 2.63	2.86 ± 2.94	<0.001
Quality of Life, EQ-5D-3L	0.266 ± 0.129	0.499 ± 0.260	0.232 ± 0.243	<0.001
Self-reported health status, VAS	49.6 ± 19.8	61.2 ± 21.4	11.7 ± 28.3	0.035

All values are mean ± SD, p-value refers to paired T-test.

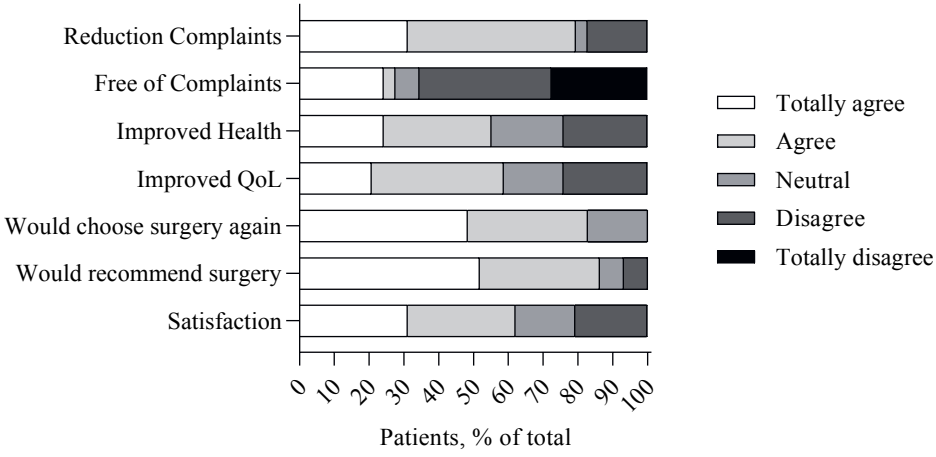

Figure 3.1 Patient's perspective on the effects of procedure.

Secondary outcome measures

Thirteen patients (44.8%) consumed opioids preoperatively. At one-year postoperatively this number decreased to seven patients (24.1%). This difference reached statistical significance (p=0.026).

Four adverse events occurred: one nerve root injury, one surgical wound infection and two cases of implant loosening. All except one patient (N=28) received a pelvic CT-scan on the first postoperative day. In 27 of 28 patients (96%), the CT-scan revealed adequate positioning of implants. The patient with nerve root injury developed complaints of radiating pain and mild paresthesia in the right leg directly after surgery. The CT-scan revealed corresponding nerve root compression of S1, caused by the most cranially located implant. However, no revision surgery was performed and complaints slowly abated during follow-up. The patient with postoperative surgical wound infection reported to the emergency department with wound leakage on the third postoperative day. Debridement surgery was performed and intravenous antibiotic (AB) therapy was administered. The patient returned home in adequate clinical condition and AB therapy was concluded for two weeks. The two cases of implant loosening were detected at subsequent CT-scans at 6- and 12-months postoperatively. Radiolucency around the affected implants was observed without any intra-articular bridging of trabeculae over the SIJ (Figure 3.2). Both patients complained of persisted SIJ pain during follow-up. Revision surgery is planned to revise the loose implants.

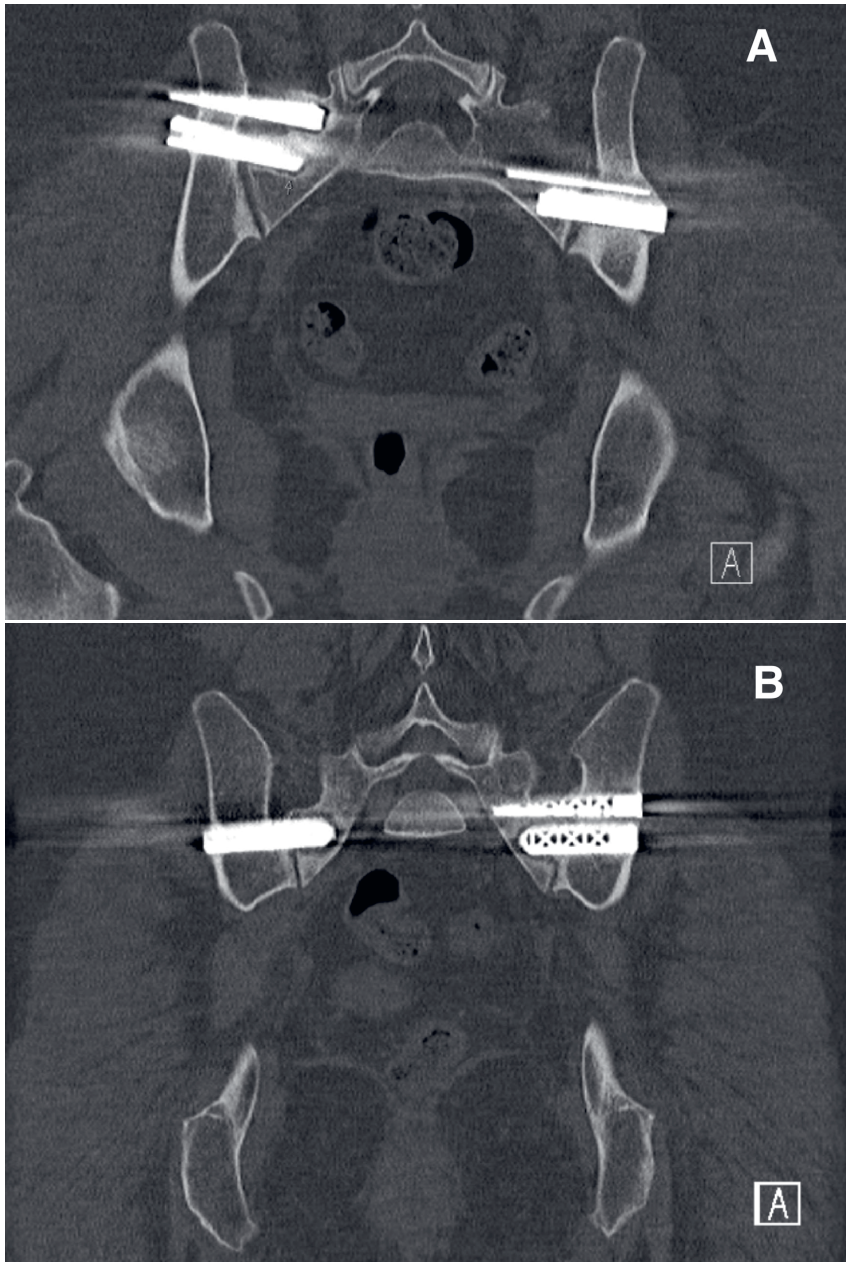

Figure 3.2 Two cases of implant loosening on pelvic CT scan. In both cases radiolucency around the implants on the right can be detected without any intra-articular bridging of trabeculae over the SIJ.

Discussion

This study provides insight on the effectiveness of MISJF in a double-center cohort in a consecutive series of patients with SIJ dysfunction. Overall, we found significant improvements in pain and quality of life, with a low rate of (serious) adverse events, one year following surgery. We report a mean VAS-pain improvement of 2.86 points and an EQ-5D-3L improvement of 0.232 points. These PROMs are accompanied with an overall satisfaction rate of 62.1%. These results are less effective when compared to some studies in the existing literature. A lot of studies report a VAS-pain improvement of around 4.5 points and satisfaction rates of around 80% following MISJF.[12,13,16,18] A potential explanation for this is that bilateral SIJ dysfunction is a common entity. Typically, there is one more symptomatic side, and in a few cases MISJF for one side is followed by MISJF on the other side because of remaining complaints. Possibly, some postoperative patients did not show significant improvements in pain and QoL as the other SIJ was still symptomatic and requires surgery as well. In our study a significant proportion of patients suffer from EDS compared to the existing literature. Patients with EDS often suffer from chronic pain as a major source of disability.[24] The difference in patient population is a potential reason for the higher pain score and lower QoL reported postoperatively. In addition, some of these studies implemented eligibility criteria as a baseline score of at least 30% on the Oswestry Disability Index and a VAS-pain score of at least 50 (0-100 scale). There are some independent studies in which the results are more in line with the findings we report in this study.[25,26]

Baseline characteristics of the present cohort show that SIJ dysfunction mostly affects younger women. In most cases the cause of SIJ dysfunction was of postpartum origin. These data are in line with previous published studies on SIJ dysfunction.[15,27,28] In the present study a significant number of patients suffer from EDS, as a cause of SIJ dysfunction. Only one case series has been published on MISJF in patients with EDS, with successful outcomes.[7] It would be interesting to see future studies focus on this population. Additional baseline characteristics reveal a high prevalence of patients consuming opioids before surgery, revealing a significant degree of pain in daily life. A recent study by Dengler et al. noted similar opioid consumption in patients with SIJ dysfunction (52.5%). Opioid consumption remained the same in the conservatively treated patients (46.9%), while it significantly decreased following MISJF (57.7% to 44.2%).[29] For comparison, opioid consumption in patients with knee or hip osteoarthritis is reported to be around 23.6%.[30] Furthermore, individuals with

postpartum SIJ pain are often unable to stay active in their workplace.[31] All these findings are in line with the high preoperative VAS-pain score of 7.83, reported in this cohort. The VAS-pain score one year following surgery was statistically significantly lower. Although, the difference seems moderate at first, it reaches the minimal clinically important difference (MCID) according to Kube et al. who defined a reduction of 2.0 points to be clinically relevant.[26] It is recommended that MCID's should be considered context-specific and take into account the level of pain at baseline.[32] Baseline VAS-pain was high in the presented cohort, which means even modest changes could be of importance. At an individual level, MCID for VAS-pain was reached in 69% of patients. The reported improvement in EQ-5D-3L score also reached MCID.[33] The mean EQ-5D-3L one year following MISJF was 0.499, which according to Whynes et al., remains to be a moderate level of daily discomfort.[34] In 72.4% of patients the MCID for EQ-5D-3L was reached. Conforming EQ-5D-3L score, the remaining VAS-pain score also suggests some level of pain still exists in our patients one year following surgery. However, according to our exploration of patient's perspective on the effects of the procedure, 62.1% of patients state to be satisfied with the clinical outcome. Even more patients (82.8%) state they would have the same surgery again knowing the outcome. This could partially be psychological, as patients have often been in long lasting and unsuccessful rehabilitation. Many of our patients have had symptoms for several years before final diagnosis of SIJ dysfunction was established. Throughout this period patients have often seen countless specialists and were treated inadequately. Therefore, surgery may feel like a last resort to them. Hence, patients expectations and wish for surgery might be increased. This may bias their interpretation of pain reduction following a diagnostic injection, resulting in poorer surgical outcomes. At the same time, patients may perhaps be more forgiving and positive towards the results of MISJF. This might partly explain the discrepancy in satisfaction and the choice to have surgery again. Around one in four patients states to be completely free of complaints one year following surgery. Therefore, expectation management plays a significant role in the treatment of SIJ dysfunction. Besides surgical treatment, a holistic approach should be considered, including psychological problems.[35]

The rate of (S)AE's in the present study population is in line with prior published studies.[15,27] Revision surgery is required in two patients were implant loosening occurred, accompanying inadequate fusion of the SIJ. No predisposing patient factors linked to implant loosening could be identified. Both patients underwent staged bilateral MISJF and implant loosening occurred

in the first operated side. Although these patients suffered an AE, they both stated that they would have surgery again. VAS-pain score improved from 8 to 7 and from 6 to 3 points, respectively. These data indicate that some relief of complaints occurred following both surgeries. Revision surgery is planned with the aim to further improve clinical outcome in these patients, as a newly performed diagnostic SIJ injection reduced complaints. We aim to remove the loose implants and place new implants in an additional trajectory. When there is no sufficient additional trajectory available, the new implant will be rotated to ensure proper fixation.

Limitations

This study is bound by some limitations. First this a retrospective study in which, not all data could be retrieved from the patient-charts resulting in exclusions, potentially leading to selection bias based on completeness of PROMs dataset. The COVID-19 pandemic was a major reason for the significant loss of preoperative PROMs, as these were not collected during this period. The sample size may seem small at first, but can be considered adequate as SIJ dysfunction is only diagnosed in few people. Furthermore, a sample size of 29 patients is in line with prior published studies on MISJF.[12,36]

Patient's perspective on the effects of the procedure were evaluated using a non-validated questionnaire. The other outcome measurements (VAS-pain and EQ-5D-3L) are validated tools. Nonetheless, they remain PROMs and are thereby at risk for some sort of subjective discrepancies. This could explain why the satisfaction rate is lower than the percentage of individuals who would have surgery again for the same results. These differences in numbers feel conflicting.

Finally, the study length of one year is short. It would be interesting to see long-term follow-up of our patients, especially when a relatively large number of patients indicates to have a neutral perspective on the effects of the procedure. Prior studies with longer follow-up showed excellent results up to six years following surgery.[37,38]

Despite the above-mentioned limitations, we were able to obtain data that is still insightful for future studies. Presently, only a few studies are available in Europe that describe the effectiveness of MISJF.

Conclusion

This independent study presents a two-center retrospective cohort of 29 consecutive patients who underwent MISJF for SIJ dysfunction. Although the sample size is limited MISJF indicates to be a safe and reasonably effective procedure, with acceptable satisfaction rates and significant improvements in pain and QoL reported one year following surgery. Future studies should focus on the long-term results to further evaluate the effectiveness of MISJF.

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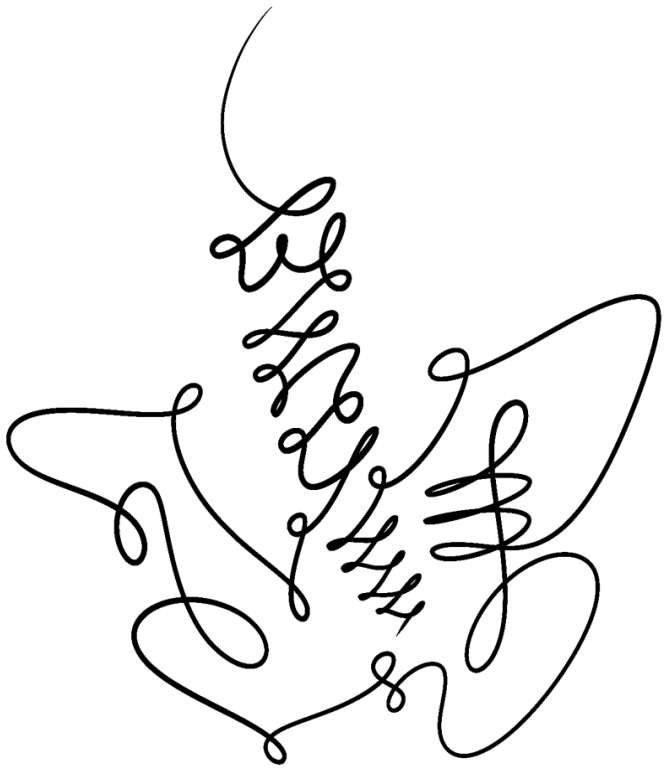
Appendix 3.1

Additional File 3.1: statements on patient's perspective on the effects of the procedure

1. I am satisfied with the result of the treatment.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
2. The complaints I experienced before the treatment have decreased.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
3. I am pain free after the treatment.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
4. My health has improved after the treatment.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
5. My quality of life has improved after the treatment.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
6. In retrospect, with the knowledge and experience I now have, I would have the same surgery for the same result.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree
7. I would recommend the treatment to patients with similar complaints.
   a. Totally agree
   b. Agree
   c. Neutral
   d. Disagree
   e. Totally disagree



Chapter 4

Accelerometer based physical activity monitoring in patients with postpartum sacroiliac joint dysfunction: A case-control study

Sem M.M. Hermans, Jasper Most, Martijn G.M. Schotanus, Henk van Santbrink, Inez Curfs, Wouter L. W. van Hemert

Submitted

Abstract

Objectives

Patients with low back pain caused by sacroiliac joint (SIJ) dysfunction have an impaired quality of life, due to reported pain, disability and activity limitations. There is increasing evidence that minimally invasive sacroiliac joint fusion (MISJF) results in improvement in pain, disability and quality of life in these patients. Some studies have reported improvements in physical activity following MISJF, but based on bias-prone self-reports. Our aim was to provide objective data on physical activity in patients with SIJ dysfunction.

Methods

Physical activity in daily life of participants was measured using triaxial accelerometer for seven consecutive days, before surgery and three months after surgery. Recorded activity were the daily number of events and total time spent sitting or lying, standing, walking, cycling, high-activity and number of steps and sit-to-stand transfers. Quality of life was assessed by the validated Dutch EQ-5D-5L-questionnaire.

Results

No statistical differences were observed between physical activity in patients with SIJ dysfunction before and three months after MISJF. As compared to matched controls, high-intensity physical activity was lower in both the pre- and postoperative period ($p=0.007$) for patients with SIJ dysfunction. Quality of life improved significantly in patients after MSIJF, from 0.418 to 0.797 ($p=0.021$), but did not reach the level of controls ($p=1.000$).

Conclusions

Physical activity in patients with postpartum SIJ dysfunction does not improve three months following MISJF, while quality of life does improve significantly. The discrepancy between these two observations is food for new research.

Introduction

Chronic musculoskeletal diseases, such as sacroiliac joint (SIJ) dysfunction, lead to physical dysfunction and inactivity.[1] Physical activity is positively associated with physical and cognitive function, and negatively associated with risk of falls and even risk of death.[2,3] To evaluate treatment efficacy for musculoskeletal diseases, it is important to monitor physical activity in individuals. Following other orthopedic treatments, e.g. hip and knee arthroplasties, physical activity improvement is surprisingly negligible, despite significant improvements in self-reported outcomes relating to physical activity.[4–7] This dissimilarity can potentially be explained by a large variability between patients, and by the fact that questionnaires are insensitive and prone to overestimation, due to subjectivity.[8]

Current literature indicates that patients with low back pain caused by SIJ dysfunction have an impaired quality of life (QoL), due to pain, disability and activity limitations.[9–11] There is increasing evidence that minimally invasive sacroiliac joint fusion (MISJF) is associated with improvement of pain, disability and QoL. One can postulate that physical activity might also improve following MISJF. Studies on self-reported physical activity suggest improvements in physical activity,[12,13] but objective data, of physical activity collected using gold-standard methodology in patients with SIJ dysfunction is not available.

In this case-controlled study, physical activity was measured in patients with postpartum SIJ dysfunction before and after MISJF and compared to age-, BMI-, gender- and postpartum-matched controls.

Material and methods

Participants

Between January 2021 and October 2021 ten patients scheduled for MISJF because of unilateral or bilateral SIJ dysfunction agreed to participate in this study. A case-controlled age and gender-matched healthy, postpartum control group (n=11) was used for comparison. All participants were informed about the study and written informed consent was obtained prior to participation. This research has been approved by the IRB of the authors' affiliated institution. Healthy participants were post-partum females aged 25 to 45 without history of SIJ dysfunction or other lower back related illness. All participants were asked to function according to their normal habits during physical activity monitoring.

Outcome

For the patient group, physical activity tracking was performed between twelve and one week(s) before surgery and three months following surgery. Control patients were measured at least six months postpartum. Physical activity in the daily life of participants was measured using triaxial accelerometer (AM; GC Dataconcepts LLC, Waveland, USA) for seven consecutive days. The AM was attached onto the lateral side of the upper leg, left or right as preferred by the participant. Based on previously published principles, accelerometer data were processed and analysed using self-constructed algorithms for feature detection and activity classification written in Matlab (MATLAB R2010a, The Mathworks Inc., Natick, Massachusetts, USA).[14–16] Activity parameters calculated were percentages of total time (duration) spent sitting or lying (inactive), standing, walking, cycling, high-activity (active) and number of steps and sit-to-stand transfers. The AM was only worn during waking hours with a minimum of eight hours a day and removed at night and during showering or other water activities. Quality of life was assessed by the validated Dutch EQ-5D-5L-questionnaire ('best health state') and the EQ self-reported health status visual analogue scale (VAS), that records the respondent's self-rated health (0–100, 100 being 'best imaginable health state').[17] EQ-5D-5L-questionnaires were completed before start of physical activity monitoring.

Statistical analysis

Statistical analyses were carried out using IBM SPSS statistics 27. Descriptive data (means, SD, proportions) were generated for all variables. Statistically significant differences between both groups were analyzed with nonparametric Mann–Whitney U test, since the group sizes were small. To compare activity parameters between groups Independent Samples Kruskal Wallis test was used. Chi-square test was used for categorical variables. A p-value ≤ 0.05 was considered statistically significant.

Results

Eight patients completed this study. Two patients were excluded as data was incomplete. The patient and control groups were statistically comparable regarding demographic characteristics (Table 4.1).

Table 4.1 Characteristics of subjects.

	Patients (N=8)	Controls (N=11)	p-value
Age (years)	43.0 (33.5:46.3)	35.0 (33.0:36.5)	0.138
BMI (kg/m2)	25.4 (23.0:30.1)	23.1 (22.2:23.9)	0.09
Number of previous pregnancies			0.173
1	1	6	
2	4	4	
3	2	1	
4	1	-	
Years postpartum	5.5 (4.1:17.0)	4.7 (3.3:5.5)	0.258

All values are median with interquartile range (1:3). P-value refers to Mann–Whitney U test or Chi-Square test for categorical variable (N pregnancies).

Before surgery, quality of life was significantly reduced in patients as compared to controls, as hypothesized. Total and low-to-medium intensity physical activity between patients and controls was not lower in patients as compared to controls. High-intensity physical activity was lower in patients.

Table 4.2 Quality of Life results.

	Preoperative (1)	Postoperative (2)	Controls (3)	p-value
EQ-5D-5L score	0.460 (0.291:0.516)	0.797 (0.691:0.818)	1.000 (1.000:1.000)	1-2: 0.021 1-3: < 0.001 2-3: < 0.001
EQ-5D-5L VAS	53 (35:61)	70 (58:85)	90 (85:93)	1-2: 0.011 1-3: < 0.001 2-3: 0.007

All values are median with interquartile range (1:3). P-value refers to Mann–Whitney U test.

Quality of life improved in patients three months postoperatively compared to preoperatively, from 0.460 to 0.797 (p=0.021). EQ-5D-5L VAS also improved from 53 to 70 (p=0.011). Postoperative EQ-5D-5L score and EQ-5D-5L VAS did not reach comparable levels to that of healthy controls (Table 4.2).
Physical activity did not increase within the patient group in any physical activity domain (Figure 4.1). Physical activity per individual shows large variability between patients (Figure 4.2).

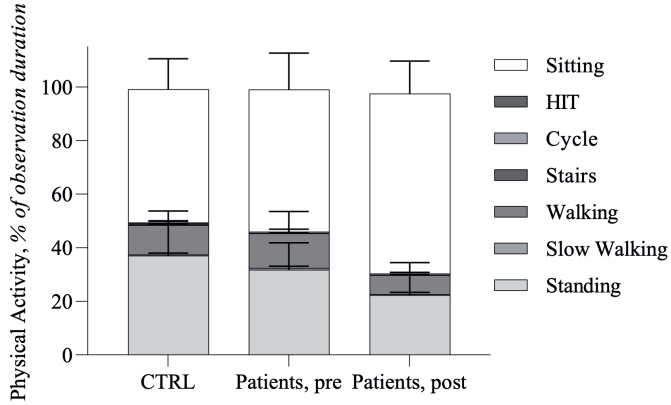


Figure 4.1 Average daily physical activity across groups. CTRL: controls, HIT: high-intensity time.

Discussion

This observational case-controlled cohort study showed that physical activity levels of patients with postpartum SIJ dysfunction did not increase three months after MISJF. This objective data also revealed that during the study period patients perform no high-intensity physical activity. Quality of life improved during the study period but did not reach level of healthy controls.

Currently, no literature exists on objective physical activity in patients with SIJ dysfunction. In a recent randomized trial, Dengler et al.[18] investigated several clinical outcomes of MISJF through questionnaires, including pain, walking distance, disability level and work status. All outcomes improved over the 24-month follow-up period. However, only pain, walking distance and disability level were already statistically significantly improved three months following MISJF. In contrast to work status, which was decreased three months postoperatively compared to preoperatively. Walking distance and work status further improved at 6-, 12- and 24-months follow-up, while pain and disability score remained stable at further follow-up moments. These data suggest that further functional improvement is expected beyond three months.

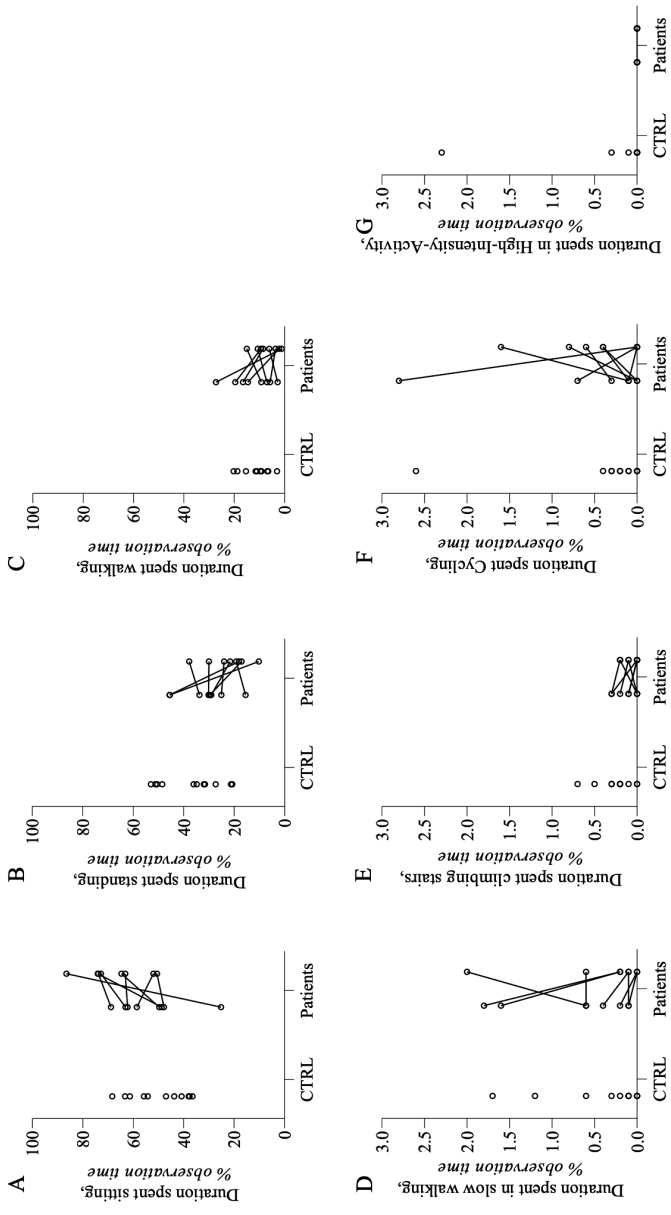


Figure 4.2 Detailed daily physical activity among individuals. In patients the changes before and after surgery are depicted. CTRL: controls.

As QoL in patients with SIJ dysfunction is comparably low to that of patients with lumbar spinal conditions, comparing available objective data on physical activity might be insightful.[10] A recent study by Coronado et al.[19] investigated physical activity in 53 patients who underwent lumbar spine surgery, 6 weeks, 3 and 6 months after surgery and found significant improvements over this time period. Another study by Gilmore et al.[20] stated that walking time in the first week after lumbar surgery is a predictor of significant improvement in function at 6 months postoperatively. In both studies no preoperative comparison was available. In patients with osteoarthritis (e.g. hip and knee) requiring arthroplasty, pre- and postoperative data are available and we know that physical activity often not improves following surgery, while health-related QoL and social mobility do.[21–23] These findings are in line with the findings of this study, as no statistically significant improvement in physical activity was observed in patients with SIJ dysfunction following MISJF, while EQ-5D-5L score improved. However, not to the level of healthy controls. As enhanced QoL is a motivator for physical activity, one may expect that both improve.[24] Potentially, the discrepancy between self-reported improvement and actual health-gain following surgery is overestimated by patients. Or perhaps the increase in QoL is a result of fewer pain complaints and not directly in enhanced physical activity.

In the current study group mean physical activity parameters for patients did not differ pre- and postoperatively. This not only means that no improvement is observed, to the contrary no deterioration is observed either. This indicates that patients with SIJ dysfunction return to their preoperative physical activity level three months following surgery, thus recovered from surgery. These physical activity levels are no different from matched controls, except for high-intensity physical activity. The latter was the only parameter that differed between patients and matched controls. High-intensity physical activity comprises sport activities. The results of this study thereby indicate that patients with postpartum SIJ dysfunction do not participate in sports.

Strength & limitations

A strength of our study is the sensor-based measurements, which gives a more reliable representation of physical activity compared to previous studies with self-reported outcomes.[18] The small sample size is a limitation of the current study and therefore this study is not appropriate for responder and non-responder analyses. The small sample size is mainly caused by strict inclusion criteria and because this study serves as a pilot study. To reduce heterogeneity

only patients with SIJ dysfunction, as a cause of previous pregnancy were included. SIJ dysfunction of post-partum origin is a prevalent cause of SIJ dysfunction, as noted in our previously published cohort study.[25] Another limitation to the current study is the short follow-up period. Three months postoperatively might be too early to expect large improvements in physical activity. Patients are still in their rehabilitation process at this time point. Furthermore, in a large number of patients bilateral SIJ complaints are present, for which a second surgery is needed, where the contralateral SIJ is fused to further alleviate complaints. In these patients further improvement can still be expected following second surgery. Figure 4.2 also indicates that changes in physical activity individually differed following MISJF. Therefore, it might be interesting to further investigate associations between patient characteristics (e.g. BMI, age, duration of complaints) and physical activity response to MISJF. Regardless of these limitations, we were able to detect differences in physical activity between patients with post-partum SIJ dysfunction and matched controls, in terms of high-intensity activity.

Conclusion

This study demonstrates that physical activity of patients with SIJ dysfunction is comparable to that of healthy matched controls, except for high-intensity physical activity which is lower in patients. Preoperative QoL is significantly lower in patients compared with matched controls. Postoperative physical activity in patients does not improve, while QoL does improve significantly, however not to the level of healthy individuals.

Acknowledgements

The authors would like to thank Mr. Leon Weem and Mr. Ivo Buil for their work in analyzing the raw data from the activity monitor.

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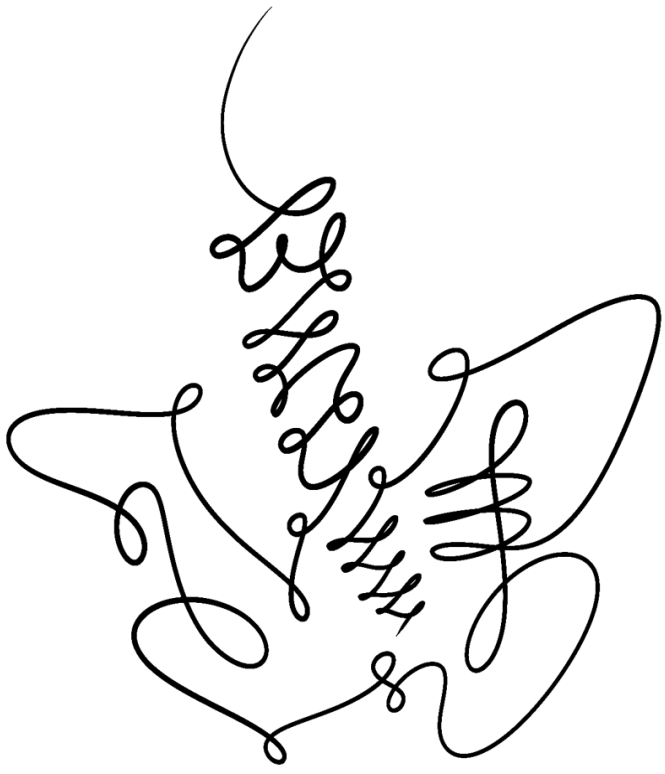

Chapter 5

Motion analysis in patients with postpartum sacroiliac joint dysfunction: A cross-sectional case-control study

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Clin Biomech (Bristol, Avon) 2022:100:105773

Abstract

Background
Patients with sacroiliac joint dysfunction are limited in daily life activities such as gait, climbing stairs and rising from a chair. It is well known that individuals with chronic low back pain have impaired balance compared to healthy individuals. This cross-sectional case-control study aims to investigate spatiotemporal parameters, center of pressure and mass, pelvic angles and other joint angles in patients with sacroiliac joint dysfunction in comparison with healthy controls.

Methods
Motion analysis existed of three tasks: (1) normal gait, (2) single-leg-stance, and (3) sit-to-stance. Spatiotemporal parameters, center of pressure, pelvic angles and other joint angles were measured using a twelve-camera, three-dimensional motion capture system and ground reaction force platforms.

Findings
Thirty subjects were recruited for this study; ten patients, ten matched controls and ten healthy student controls. For gait, patients had a lower cadence, longer double support phase, shorter step length and slower walking speed than controls. For single-leg-stance, patients had a smaller hip angle of the risen leg than controls. Also, variability in center of pressure was larger in patients. For sit-to-stance, the total time to perform the task was almost doubled for patients compared to controls.

Interpretation
This study demonstrates that patients with sacroiliac joint dysfunction have an impaired gait, more balance problems during standing and standing up compared to healthy controls. This novel information assists to further comprehend the pathology and disease burden of sacroiliac joint dysfunction, in addition, it may allow us to evaluate the effect of current therapies.

Introduction

The sacroiliac joint (SIJ) is increasingly being recognized as a potential cause of chronic low back and buttock pain. The SIJ is affected in 14-22% of the patients presenting with this pain.[1,2] SIJ dysfunction is known to be present in patients with axial spondylarthritis or osteoarthritis, but can also occur posttraumatic, post-partum, in patients with connective tissue disease or following lumbar fusion surgery.[3,4] Most patients with SIJ dysfunction suffer from localized pain around the SIJ, often radiating into the lower extremity.[5] Due to these complaints, patients experience great limitations in activities of daily life such as gait, climbing stairs or sit-to-stand tasks. The inability to perform such activities negatively affects life participation and quality of life.[6]

It is well known that individuals with chronic low back pain have poorer balance and altered motion patterns compared to healthy individuals.[7,8] In many cases this is the consequence of avoiding movements that provoke pain.[9] Patients with SIJ dysfunction may thus have altered motion patterns as well, considering the similar symptomatology. However, motion analysis in SIJ dysfunction is scantily described in the current literature. A small cohort study describes differences in balance and sagittal sacropelvic morphology in patients with or without SIJ pain following lumbar fusion.[10] A more recent study evaluated motion patterns in six patients with SIJ dysfunction performing a sit-to-stance task.[11] They concluded that patients with SIJ dysfunction load the unaffected leg and experience a larger peak hip moment on the affected side. The consequence of these alterations may lead to abnormal joint loading, which is a critical risk factor for joint degeneration, and potential complaints elsewhere.[12] This study may ameliorate and/or give new insights on the existing knowledge as we aimed to compare spatiotemporal parameters, center of pressure and mass, pelvic angles and hip and knee joint angles of patients with SIJ dysfunction with healthy controls during predefined tasks, including gait, single leg stance and sit-to-stance tasks. We choose to include single leg stance, as this is often used as a diagnostic test in SIJ dysfunction.[13]

Methods

Study design

This was a prospective, cross-sectional pilot study to compare patients with SIJ dysfunction to healthy age-matched controls and healthy younger controls. This

study was registered in the Clinical Trial Register (registration number: NCT04824534) and was written in accordance with the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) guidelines.[14] Ethical approval of this study was obtained by the METC Z (registration number: METCZ20210010) at Zuyderland Medical Center and Zuyd University of Applied Sciences (Heerlen, the Netherlands). The inclusion period lasted from January 2021 until October 2021. All subjects were informed on the purpose of the study and gave written informed consent before participation.

Participants

Consecutive patients were recruited by physicians specialized in SIJ dysfunction at the Department of Orthopedic Surgery and Traumatology at Zuyderland Medical Center, (Heerlen, the Netherlands). For this prospective cohort study, ten female patients aged 18 years and older with uni- or bilateral diagnosed SIJ dysfunction as a result of post-partum pelvic instability were included. SIJ dysfunction was diagnosed based on history, physical examination and confirmed by an image-guided injection into the SIJ with local anesthetic resulting in a >50%-reduction of pain. Patients were excluded if they were unable to perform more than one of the tasks needed to obtain the correct data and/or if they had inadequate command of the Dutch language.
Control subjects were recruited at Zuyd University of Applied Sciences (Heerlen, the Netherlands) and by the Department of Orthopedic Surgery and Traumatology at Zuyderland Medical Center (Heerlen, the Netherlands). Two control groups are used in this study and existed of a "matched control group for demographic characteristics" and a "student control group". For the matched control group, ten healthy post-partum females aged 25 to 45 without history of SIJ dysfunction or other lower back related illness were included. For the student control group, ten healthy females under the age of 25 without history of SIJ dysfunction, other lower back related illness or previous pregnancies were included.

Motion analysis tasks

All motion analyses were performed at the motion lab at Zuyd University of Applied Sciences (Heerlen, the Netherlands). Height, weight, leg dominance, leg length, ankle width, knee width, hand thickness, wrist width and elbow width were measured as previously described.[15] Quality of life was assessed by the validated Dutch EQ-5D-5L-questionnaire (-0.329 to 1.00, 1.00 indicates 'best

health state') and the EQ self-reported health status, visual analogue scale (VAS), that records the respondent's self-rated health (0 - 100, 100 being 'best imaginable health state').[16] Motion analysis existed of three tasks: (1) normal gait, (2) alternated single leg stance (SLS), and (3) sit-to-stance (STS).

For normal gait task, subjects were asked to walk at self-selected normal speed. The walk had to be repeated until each foot landed (heel-strike to toe-off) on one of the force plates as information collected by these force plates was used in the analyses. A minimum of one correct measurement had to be performed to collect sufficient data. To avoid deviations from normal gait, subjects were not aware of the presence of the force plates.

For SLS task, subjects were standing with each foot on one of the force plates. They were asked to rise one leg to 90° hip and knee flexion, hold this position for ten seconds, and lower it back to the ground again. The task was repeated with the opposite leg. Subjects had to redo the task up to three times.

For STS task, subjects sat on a stool with 90° hip and knee flexion with their feet at shoulder width on one of the two force plates and their arms stretched forward. They were asked to stand up (without using their arms), pause for 2 seconds, and sit down again. One test trial was performed to get familiar with the movement. A minimum of two correct measurements were performed.

For all tasks, the cycle with adequate execution of the task and the most captured motions (with fewest gaps to fill) was chosen for final analysis.

Data collection

Motion analysis on gait, SLS and STS tasks was performed using a twelve-camera, three-dimensional motion capture system (Vicon, MX3, Oxford Metric, UK) in combination with Nexus 2.11 software. For this, 39 reflective markers were placed according to the PlugInGait FullBody Ai model (Additional file 5.1-5.3 in Appendix 5.1).[17] Placement of markers was always performed by one of two researchers (SH and EP). The ground reaction force (GRF) was measured by two force platforms (Gen 5 signal conditioner, AMTI force and motion, MA, USA). GRF was normalized for body mass. For all tasks the cycle with the most captured motions was analyzed. Gaps in trajectories were managed with cycle fill. If cycle fill was not available spline, patterns or rigid body fill was used. Sampling rates of motion capture markers was 100Hz and 1000Hz for force plate acquisition.

Data analysis

Gait was analyzed for two strides according to the phases of the gait cycle and normalized to 100% of the task.[18] Spatiotemporal parameters of interest were cadence, double support phase, single support phase, step length, step time, step width, stride length, stride time and walking speed.

Regarding the SLS task, parameters of interest were pelvic obliquity, hip angle of the risen leg, knee angle of the standing leg and variability in center of pressure and center of mass. In brief, pelvic obliquity is the movement of pelvic rotation in the frontal plane (abduction/adduction), as derived from the waist markers. Further description has been described elsewhere.[15] Center of mass was calculated from a subject-specific anatomic model which was created with marker data and anthropometric measurement from Vicon. Applying the concept that the mean center of pressure and center of mass in the anterior-posterior and medial-lateral direction should be coincident, an offset was computed and applied to the center of mass time series data.[19] To illustrate these data we created stabilographs in which the deviations from the local average center of pressure and center of mass with corresponding trajectory were plotted.[20] Variability in anterior-posterior and medial-lateral range deviation from local average, also known as postural sway, provides an indication of (in)balance.[21–23]

For the STS task, the movement was divided into three phases based on joint kinematic events: leaning phase (start – maximal hip flexion), momentum phase (maximal hip flexion – maximal ankle dorsiflexion) and extension phase (maximal ankle dorsiflexion – maximal hip extension).[24] For analysis, tasks were normalized to 100%. Parameters of interest were total time with subphase duration and load capacity of both legs.

All data were processed in MATLAB and Statistics software (Toolbox Release 2017b, The MathWorks, Inc., Natick, Massachusetts, US) and Polygon software (Vicon, MX3, Oxford Metric, UK) to generate the abovementioned parameters of interest.

Statistical analysis

Statistical analyses were carried out using IBM SPSS statistics 27 (Inc., Chicago, IL). All descriptive data were presented as means with standard deviations (SD), frequencies (%) or medians with interquartile ranges (IQ) in case of non-normal distribution. Descriptive data were generated for all variables and all data was tested for normal distribution. To compare the three groups (patients, age-

matched controls, young controls), univariate analysis was performed for baseline characteristics. In non-normal distribution Kolmogorov-Smirnov Z-test was used. Categorical data was assessed using Chi-Square test. To compare more than two independent samples, Kruskal Wallis one-way ANOVA test was used. A p-value ≤ 0.05 was considered statistically significant.

Results

Thirty subjects were included in this study. Baseline characteristics are outlined in Table 5.1. No statistically significant differences were observed between patients and matched controls in terms of age, BMI, number of pregnancies and years postpartum. EQ-5D-5L score and EQ-VAS were statistical significantly lower in patients with SIJ dysfunction. For student controls, age differed from other study groups and EQ-5D-5L score and EQ-VAS did not differ from matched controls.

Table 5.1 Baseline characteristics of subjects .

	Patients with SIJ dysfunction (1) (n=10)	**Matched control group (2) (n=10)**	**Student control group (3) (n=10)**	**p-value**	**Pairwise comparison of groups**
Age (years)	38.5 (31.8-45.0)	34.5 (31.8-36.0)	19.0 (18.0-20.0)	< 0.01	1-2: 0.460 1-3: <0.001 2-3: <0.001
BMI (kg/m2)	25.4 (22.7-32.7)	22.7 (21.8-23.7)	22.7 (18.6-24.0)	0.62	N.a.
Number of pregnancies	2 (1-3)	1 (1-2)	N.a.	0.143	N.a.
Years postpartum	5.5 (4.0-21.5)	4.0 (1.3-5.5)	N.a.	0.075	N.a.
EQ-5D-5L score	0.404 (0.167-0.516)	1.000 (0.969-1.000)	1. 000 (0.961-1.000)	< 0.01	1-2: <0.001 1-3: <0.001 2-3: 1.000
EQ-5D-5L VAS	47 (24-61)	90 (84-95)	88 (79-95)	< 0.01	1-2: <0.001 1-3: <0.001 2-3: 0.769

All values are medians with interquartile range (1-3). P-value refers to Kruskal Wallis one-way ANOVA test between study groups. N.a.: when no statistical difference is reached no pairwise comparison of groups is performed.

Gait

At self-selected pace, patients with SIJ dysfunction had a lower cadence in comparison to matched controls and student controls. Patients walked with a longer double support phase and with a shorter step length. Step time and stride time were longer in patients and a slower walking speed was noted in comparison to the matched controls and student controls. There was no

difference in single support phase between study groups. Outcomes of gait analysis between the matched control group and student control group were similar except for stride length, this was larger in the student group. Complete outcomes of gait analysis are outlined in Table 5.2.

Table 5.2 Outcomes of gait analysis.

	Patients with SIJ dysfunction (1)	Matched control group (2)	Student control group (3)	p-value	Pairwise comparison of groups
Cadence (steps/min)	101 (91-104)	116 (114-120)	114 (111-120)	0.001	1-2: 0.001 1-3: 0.022 2-3: 1.000
Double support phase (s)	0.33 (0.30-0.35)	0.21 (0.19-0.21)	0.21 (0.19-0.23)	0.001	1-2: 0.022 1-3: 0.001 2-3: 1.000
Single support phase (s)	0.44 (0.43-0.50)	0.41 (0.40-0.42)	0.42 (0.40-0.44)	0.061	N.a.
Step length (m)	0.56 (0.53-0.59)	0.66 (0.64-0.71)	0.67 (0.64-0.68)	0.001	1-2: 0.001 1-3: 0.001 2-3: 1.000
Step time (s)	0.59 (0.58-0.66)	0.51 (0.50-0.53)	0.54 (0.51-0.55)	<0.001	1-2: <0.001 1-3: 0.022 2-3: 1.000
Step width (m)	0.15 (0.14-0.16)	0.12 (0.11-0.16)	0.11 (0.10-0.13)	0.001	1-2: 1.000 1-3: 0.001 2-3: 1.000
Stride length (m)	1.11 (1.06-1.20)	1.32 (1.30-1.42)	1.34 (1.30-1.36)	<0.001	1-2: 0.022 1-3: 0.001 2-3: <0.001
Stride time (s)	1.19 (1.15-1.32)	1.03 (1.00-1.05)	1.06 (1.01-1.08)	0.003	1-2: 0.001 1-3: 0.022 2-3: 1.000
Walking speed (m/s)	0.96 (0.80-1.05)	1.33 (1.23-1.41)	1.26 (1.21-1.30)	<0.001	1-2: <0.001 1-3: <0.001 2-3: 1.000

All values are medians with interquartile range (1-3). P-value refers to Kruskal Wallis one-way ANOVA test between study groups. N.a.: when no statistical difference is reached no pairwise comparison of groups is performed.

Single leg stance

Patient with SIJ dysfunction reached a smaller hip angle than matched controls and student controls during a SLS. No study group reached a mean of 90°, as was instructed. Complete data regarding pelvic obliquity angle, hip angle and knee angle during SLS are described in Table 5.3. In Figure 5.1 and 5.2 the mean hip angle during SLS of all study groups are depicted.

Table 5.3 Outcomes of SLS.

	Patients with SIJ dysfunction (1)	Matched control group (2)	Student control group (3)	p-value	Pairwise comparison of groups
Pelvic obliquity L (°)	10.1 (7.2-12.9)	9.5 (8.0-12.4)	10.0 (8.9-13.9)	0.463	N.a.
Pelvic obliquity R (°)	11.5 (6.9-16.3)	7.9 (5.5-10.3)	9.5 (8.0-11.4)	0.073	N.a.
Hip angle L (°)	76.9 (72.1-80.3)	84.2 (81.1-87.0)	89.5 (86.1-93.9)	0.006	1-2: 0.226 1-3: 0.004 2-3: 0.487
Hip angle R (°)	71.1 (67.8-75.9)	83.4 (79.4-86.9)	88.5 (79.9-91.9)	0.002	1-2: 0.047 1-3: 0.002 2-3: 1.000
Knee angle L (°)	17.7 (7.8-21.0)	13.8 (7.2-16.4)	14.6 (10.5-18.4)	0.907	N.a.
Knee angle R (°)	15.1 (12.4-20.3)	14.8 (12.8-16.3)	16.4 (11.6-19.7)	0.671	N.a.

All values are means with standard deviation. P-value refers to Kruskal Wallis one-way ANOVA test between study groups. N.a.: when no statistical difference is reached no pairwise comparison of groups is performed.

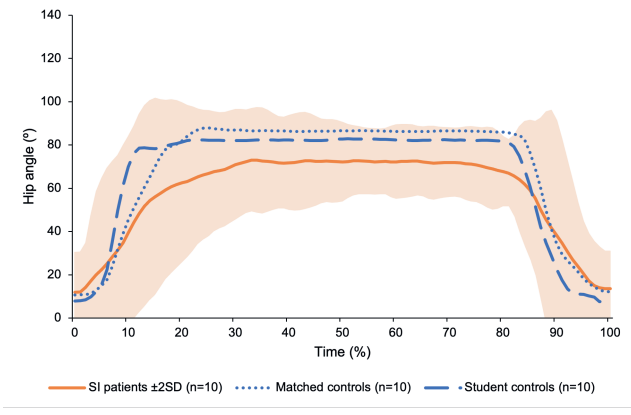

Figure 5.1 Mean right hip angle during SLS of patients and controls.

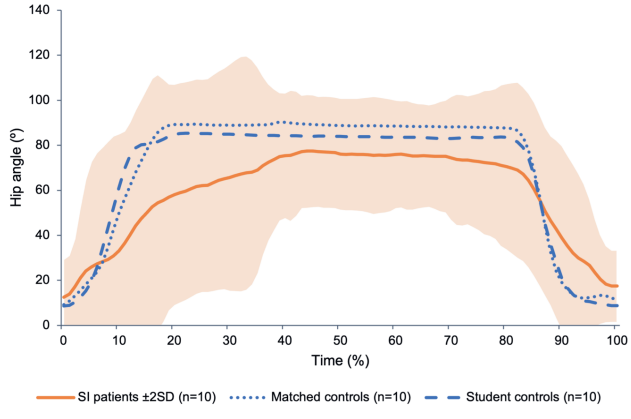

Figure 5.2 Mean left hip angle during SLS of patients and controls.

Variability in center of pressure and center of mass during SLS between study groups is depicted in stabilographs (Figure 5.3). For center of pressure, the mean medial-lateral range for right side differed between patient group and matched control group (p=0.013). Center of mass medial-lateral and anterior-posterior range and center of pressure anterior-posterior range were not statistically significant different between groups.

Sit-to-stance

For the momentum phase, patients were slower than student controls and for total time of STS patients were slower than matched controls and student controls. Between the relative contribution of all sub-phases no differences were noted between groups. One patient was unable to perform STS task, as she was unable to get up from the stool without using her hands.

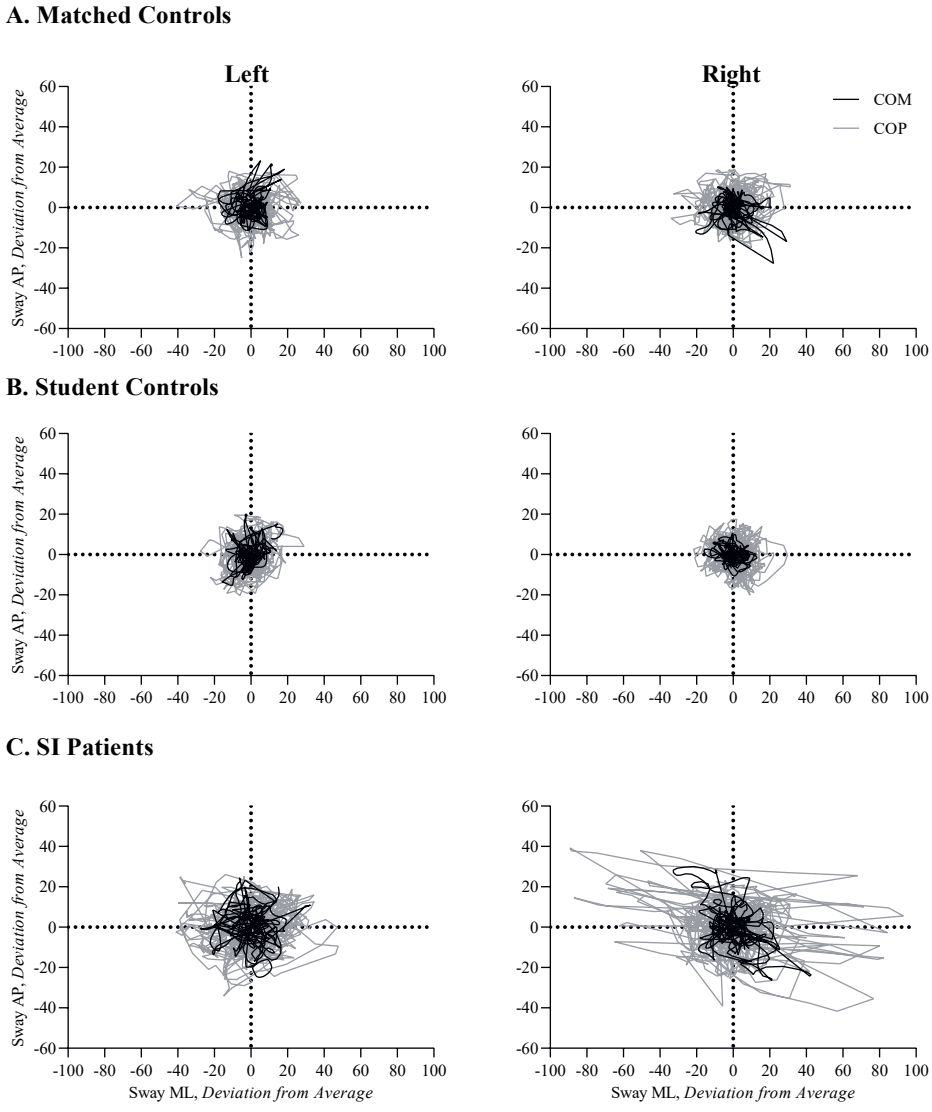

Figure 5.3 Stabilographs of study groups during SLS. COP L: center of pressure left, COM L: center of mass left, COP R: center of pressure right, COM R: center of mass right.

Table 5.4 Outcomes of STS.

	Patients with SIJ dysfunction (1)	Matched control group (2)	Student control group (3)	p-value	Pairwise comparison of groups
Leaning phase (s)	1.11 (0.97-1.31)	0.66 (0.58-0.78)	0.69 (0.63-0.74)	0.093	N.a.
Leaning (%)	31.2 (28.7-40.7)	35.9 (34.1-40.5)	36.0 (34.0-42.0)	0.263	N.a.
Momentum phase (s)	0.37 (0.30-0.56)	0.20 (0.17-0.25)	0.26 (0.20-0.29)	0.009	1-2: 0.119 1-3: 0.035 2-3: 0.533
Momentum (%)	11.3 (9.2-18.4)	9.8 (8.7-14.5)	14.0 (10.0-15.0)	0.903	N.a.
Extension phase (s)	1.83 (1.70-2.37)	0.89 (0.84-1.01)	0.94 (0.88-1.05)	0.093	N.a.
Extension (%)	51.6 (49.4-62.9)	50.8 (46.6-54.3)	50.0 (45.0-51.0)	0.199	N.a.
Total STS time (s)	3.41 (3.11-4.57)	1.92 (1.69-1.99)	1.97 (1.82-2.05)	0.009	1-2: 0.002 1-3: 0.002 2-3: 1.000

All values are medians with interquartile range (1-3). P-value refers to Kruskal Wallis one-way ANOVA test between study groups. N.a.: when no statistical difference is reached no pairwise comparison of groups is performed.

Discussion

Pain emanating from the SIJ remains an under-recognized cause of chronic low back and buttock pain.[25] Patients with SIJ dysfunction have an impaired quality of life, with sufferers commonly reporting pain, disability and activity limitations.[6,26] The aim of this study was to investigate motion patterns in patients with SIJ dysfunction predefined tasks. The most important finding is that differences in movement patterns can be observed between patients with post-partum SIJ dysfunction compared to healthy controls, existing of matched controls and student controls. Data from the student controls indicate that differences measured in parameters are not conditional to age or postpartum factors.

A disturbed gait with a slower walking speed and longer double support phase were some of the abnormalities we demonstrated in patients with SIJ dysfunction compared to matched controls. According to current literature, pain in the lower back alters muscle activation patterns during walking, potentially explaining the differences demonstrating in this study.[27] The longer double support phase indicates that patients prefer to keep both feet on the ground, potentially because of discomfort in the pelvic area or issues regarding balance. Likewise, step length is reduced in patients compared to matched controls. As Hueng et al. observed, individuals with chronic low back pain tend to use more

pelvic rotation to maintain step length.[28] One can postulate that patients with SIJ dysfunction avoid pelvis rotation, thus decreasing step length. No differences were measured between matched controls and student controls, except for stride length, indicating a similar gait.

The mean hip angle of the risen leg was significantly lower during SLS in patients compared to the control groups. To perform a SLS, lumbosacral involvement is essential and by decreasing the hip angle of the risen leg, less pelvic obliquity is required. This is a potential explanation for the lack of difference in pelvic obliquity between groups. This is in contrast to the experience that patients with SIJ dysfunction often suffer from gluteus medius weakness, contributing to SIJ pain.[29] Figures 5.1 and 5.2 show the difference in hip angle during SLS task execution between the study groups. Furthermore, a more gradual incline in hip angle during execution is present in the patients group as compared to the control groups. One can hypothesize that the difficulty and inability to rise the leg to a hip angle of 90° might be due to lack of balance. It is visually apparent in the stabilographs that patients had a larger sway during SLS. However, only the mean right medial-lateral range for center of pressure statistically significantly differed between the patient and matched control group. Potentially, a larger sample size is needed to reach statistical significance in other ranges (e.g. anterior-posterior range). Although differences in left and right side are referred to a few times in this paper. We did not differentiate between uni- or bilateral SIJ dysfunction, as often both joints are effected in SIJ dysfunction as a result of pregnancy.[30] This phenomenon can be explained by the release of relaxin hormone during pregnancy causing the ligaments surrounding the SIJ to loosen, compromising muscle stability, resulting in increased demand of both joints.[31] In patients with SIJ dysfunction the complaints associated with these changes do not resolve following pregnancy, resulting in chronic SIJ pain.[32] Typically, one SIJ is more symptomatic, and often, MISJF for one side is followed by MISJF on the other side. In this cohort the most affected side was evenly distributed, five patients reported the left side to be most symptomatic and five the right side. As for leg dominance during SLS, there is no clear lateral dominance in postural stability.[33,34] Therefore, we did not investigate differences in subjects leg dominance.

Patients with SIJ dysfunction have an almost doubled total STS time compared to matched controls (3.41 vs. 1.92s). The relative contribution of all sub-phases were not statistical significantly different between groups. Duration of the extension phase contributed most to STS duration in all groups (47.57 to

55.11%). In previous research it was noted that patients with SIJ dysfunction have a greater peak hip moment in the unaffected leg and use a smaller range of motion at the hip joint of the affected leg.[11] As these studies refer to one affected leg, it is expected that the included patients suffer from unilateral SIJ dysfunction. In the present study we included patients with predominantly bilateral SIJ dysfunction. A reasonable explanation for the increased duration of STS in our patients might be derivative from pain avoidance or lack of strength. By gradually performing STS, especially in the extension phase, the amplitude and velocity of painful motion might be reduced. Noteworthy, one patient was unable to perform an STS without using her hands, as it was too painful. This patient was not included in the data analysis of STS task. Figure 5.4 indicates notable, yet unsignificant, differences in GRF between both legs in patient group as compared to control groups. This demonstrates that the load capacity is not evenly distributed across both legs, while this is the case in healthy individuals.[11]

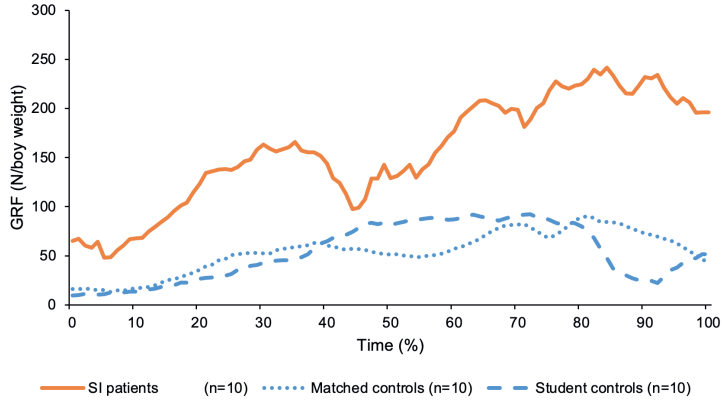

Figure 5.4 Absolute left-right difference in GRF during STS across study groups. GRF; ground reaction force, N; Newton (kg m s^{-2}).

It is important to evaluate motion patterns in patients with musculoskeletal disorders. SIJ dysfunction remains a painful condition in which patients often report a decreased quality of life.[25] In this study, a low mean EQ-5D score of 0.404 was observed, which is comparable to the current literature.[6] According to a recent review performed by Martin et al. patients with SIJ dysfunction have a mean Oswestry Disability Index (ODI) score of 56.2, which is interpreted as severe disability.[35,36] In some patients, we aim to improve the quality of life and

disability experienced by performing MISJF. Three months following surgery we will perform motion analysis again to evaluate the effect of surgery on movement patterns. Potentially these data contribute to the development of specialized rehabilitation programs for patients with SIJ dysfunction.

Limitations

This study is bound by several limitations. The most important limitation is the limited number of patients and power of this study. Nevertheless, this study was carried out in order to better understand motion patterns in a homogenous group of patients with post-partum SIJ dysfunction and well-matched controls. We chose to solely include patients with SIJ dysfunction of post-partum origin as this is one of the leading causes of SIJ dysfunction.[37] Furthermore, by focusing on one etiology of SIJ dysfunction we are able to reduce heterogeneity, which is important in a small cohort. Despite the limited sample size, we were able to detect differences in motion patterns between patients with post-partum SIJ dysfunction compared to healthy controls. Still, we feel some outcomes between study groups did not reach statistical significance because of lack of power. As an example, Figures 5.1, 5.2 and 5.3 all suggest a lack of balance in the patient group. Nevertheless, no statistical differences could be demonstrated.
Second, a selection bias exists as patients were excluded if they were unable to perform more than one of the tasks needed to obtain the correct data. Because of this, one patient was unable to participate in the present study. A small group of patients treated for SIJ dysfunction in our center is (partly) wheelchair bound. This group is not included in this study. In the presented patient group it was also difficult to collect larger amounts of data, as for some patients it was challenging to perform one adequate task, such as gait or STS. This is also one of the reasons why only one cycle was analyzed per task.
Finally, markers for capturing motion were placed on clothing and not on skin. It is known that this can give a potential error in pelvic kinematics, as well as hip kinematics.[38] We tried to minimize this limitation by dressing the subjects in tight fitting clothing, provided at the lab.[39]

Conclusion

This study demonstrates that patients with post-partum SIJ dysfunction have a disturbed gait, more lack of balance during a SLS, and a slower STS compared to healthy controls. This novel information assists to further comprehend the

pathology and burden of disease in SIJ dysfunction. In addition, it may allow us to evaluate the effect of different therapies.

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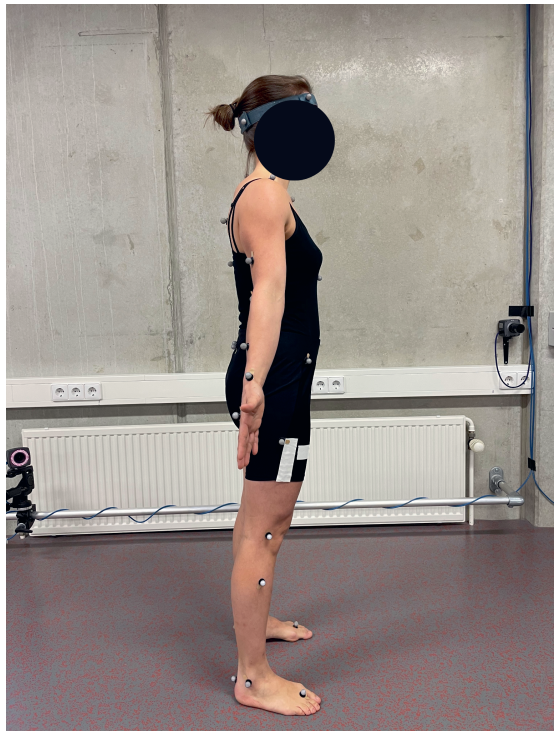
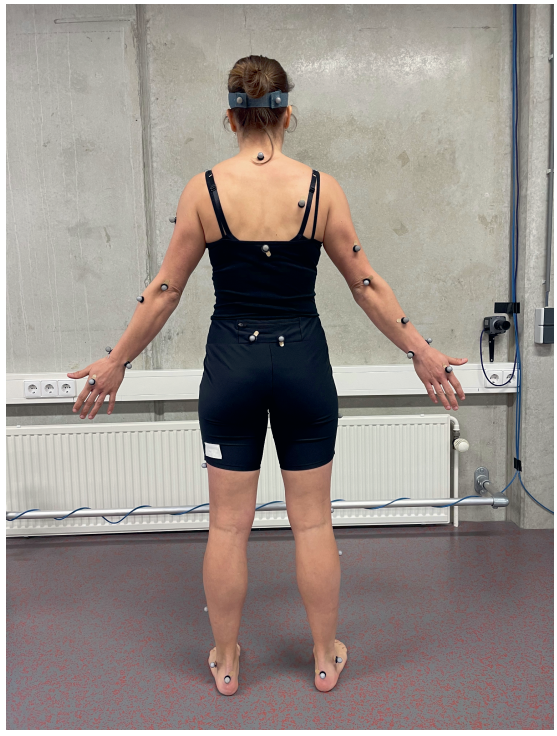
Appendix 5.1

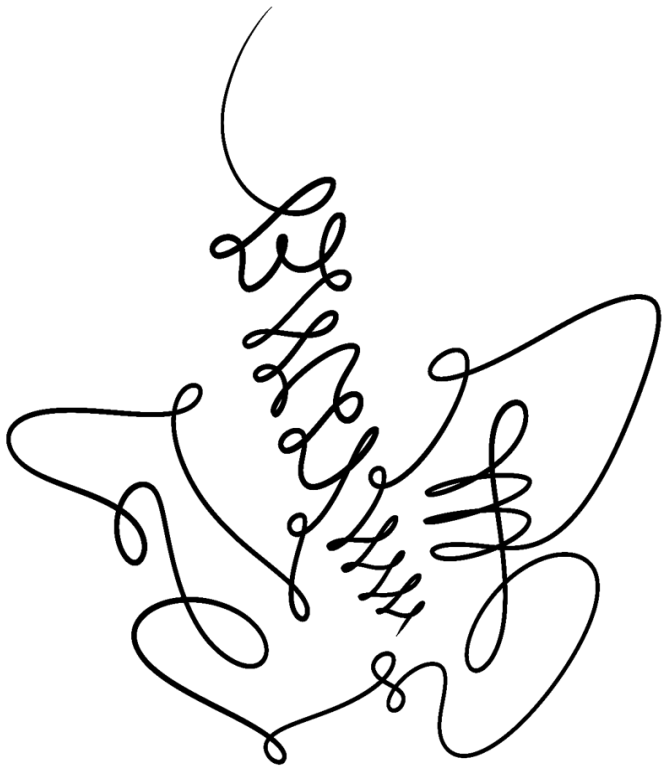
Additional file 5.1: Full body model Vicon front

Additional file 5.2: Full body model Vicon side



Additional file 5.3: Full body model Vicon back





Chapter 6

Motion analysis after minimally invasive sacroiliac joint fusion in patients with postpartum sacroiliac joint dysfunction: An observational case-control study

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J Orthop Ther, accepted

Abstract

Introduction

The sacroiliac joint (SIJ) can be an important and significant cause of low back pain. A dysfunctional SIJ is initially treated with conservative treatment options, although known to have limited effectiveness and durability. Therefore, surgical approaches such as minimally invasive sacroiliac joint fusion (MISJF) have emerged and outcomes appear to be promising in terms of pain reduction and improvement of self-reported mobility. To date, little is known about the effects of MISJF on balance and motion patterns reflective of daily life activities.

Methods

A prospective, longitudinal study was conducted to analyze motion patterns in patients with postpartum SIJ dysfunction before and three months after MISJF, and compare these data with age-, BMI- and postpartum-matched controls. Motion was analyzed throughout the execution of three tasks; (1) normal gait, (2) alternated single leg stance (SLS), and (3) sit-to-stance (STS). Spatiotemporal parameters, center of pressure and mass, pelvic angles and other joint angels were measured using a twelve-camera, three-dimensional motion capture system and ground reaction force platforms.

Results

Gait analysis revealed no improvement in any of the measured parameters when comparing pre- and postoperative. Patients had a shorter step and stride length and a slower walking speed compared to matched controls. During SLS, improvements in balance were observed after surgery in the patient group, reaching comparable values to the matched control group. Total execution time of an STS improved in patients following MISJF and was comparable to that of matched controls.

Conclusion

This study suggests that motion patterns seem to improve after MISJF in patients with postpartum SIJ dysfunction. Most notable differences were an improved balance during SLS and a faster STS performance. Additional studies with longer follow-up and larger sample sizes should provide more detailed insights on motion analysis in patients with postpartum SIJ dysfunction following MISJF.

Introduction

The sacroiliac joint (SIJ) can be an important and significant cause of low back pain.[1,2] Patients with SIJ dysfunction experience a high burden of disease, which is comparable to other common orthopedic conditions, such as hip and knee osteoarthritis, degenerative spondylolisthesis and spinal stenosis.[3] In all cases, SIJ dysfunction is initially treated with conservative measures such as oral analgesic use, physical therapy, pelvic compression belts, radiofrequency denervation and intraarticular steroid injections.[4–8] Since conservative treatment options are known to have limited effectiveness and durability, surgical approaches such as minimally invasive sacroiliac joint fusion (MISJF) are on the rise.[9,10] The initial outcomes of MISJF are promising in terms of pain reduction and improvement of self-reported mobility.[11] Currently, little is known about the effects of MISJF on (dynamic) balance and motion patterns reflective of daily life activities. Previously, we demonstrated that patients with postpartum SIJ dysfunction have impaired motion patterns compared to healthy controls.[12] As such, we observed a disturbed gait, with a slower walking speed and longer double support phase, balance problems during a single leg stance (SLS) and a slow sit to stance (STS) performance.
The aim of this study is to evaluate whether these observed disturbances improve three months after MISJF in patients with postpartum SIJ dysfunction. The following research question was formulated; is there a difference in spatiotemporal parameters, center of pressure and mass, pelvic angles and hip and knee joint angles in patients with SIJ dysfunction before and three months after MISJF at predefined tasks, including gait, SLS and STS.

Materials and methods

Study design

This was a prospective, longitudinal study to analyze motion patterns in patients with SIJ dysfunction before and three months after MISJF, and compare these data with matched controls. Baseline conditions, motion analysis tasks, data collection and data analysis were described in detail in a previous publication.[12] Three months following MISJF surgery, patients returned to the motion lab to re-perform motion tasks (gait, SLS and STS) and report quality of life. Quality of life was assessed by the validated Dutch EQ-5D-5L-questionnaire (-0.329 to 1.00, 1.00 indicates 'best health state') and the EQ self-reported health

status, visual analogue scale (VAS), that records the respondent's self-rated health (0 - 100, 100 being 'best imaginable health state').[13] Motion analysis existed of three tasks: (1) normal gait, (2) alternated single leg stance (SLS), and (3) sit-to-stance (STS).
This study was registered in the Clinical Trial Register (registration number: NCT04824534) and was written in accordance with the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) guidelines.[14] Ethical approval of this study was obtained by the METC Z (registration number: METCZ20210010) at Zuyderland Medical Center and Zuyd University of Applied Sciences (Heerlen, the Netherlands). All subjects were informed on the purpose of the study and gave written informed consent before participation.

Intervention

Final diagnosis of SIJ dysfunction was based on physical examination and at least a 50% reduction of SIJ pain 30 to 60 minutes following fluoroscopy-guided injection with lidocaine 2%. If eligible, patients were treated with MISJF using a series of triangular titanium, porous titanium plasma spray coated implants (iFuse Implant System®; SI-BONE, Inc., San Jose, CA, USA). After administration of general anesthesia, the patient was placed in prone position. During MISJF, intraoperative fluoroscopy was used for optimal placement of implants. A lateral incision was made across the sacral midline. Under lateral fluoroscopy view the first guide pin was positioned at the appropriate starting point. Pelvic in- and outlet view were used to place the guide across the ilium and across the SIJ until correct dept was reached. Length of the implant was measured. Subsequently a drill followed by a triangular broach were used to decorticate the bone and prepare the pathway to receive the first implant. This implant was mostly seated within the sacral ala. Same procedure was repeated for the second and third implant. The second implant was generally located above or adjacent to the S1 foramen and the third between the S1 and S2 foramen. Because of the highly variable anatomy of the SIJ, implant location may differ between patients. The incision was then irrigated with saline and the tissue layers were sequentially closed.

Statistical analysis

Statistical analyses were carried out using IBM SPSS statistics 27 (Inc., Chicago, IL). Descriptive data were generated for all variables and all data were tested for

normal distribution. All descriptive data were presented as frequencies (%) or medians with interquartile ranges (IQ), as Shapiro-Wilk-tests demonstrated non-normal distribution. To compare data between groups linear mixed models were used with postoperative measurements as reference. Categorical data was assessed using Chi-Square test. A p-value ≤ 0.05 was considered statistically significant.

Results

This study included ten patients and ten matched controls. One patient was lost to follow-up, as she waived surgery. No intra- or postoperative complications are reported. Patient demographics are summarized in Table 6.1. Quality of life and self-reported health status improved statistical significantly following surgery (Table 6.2).

Table 6.1 Characteristics of subjects.

	Patients	Matched controls	p-value
Age (years)	40.0 (33.0:44.0)	34.5 (31.8:36.0)	0.107
BMI (kg/m2)	27.9 (22.8:32.2)	22.7 (21.8:23.7)	0.095
Number of previous pregnancies			0.508
One	2	6	
Two	4	3	
Three	2	1	
Four	1	-	
Years postpartum	12.4 (4.7:20.5)	4.0 (1.3:5.5)	0.187

All values are median with interquartile range (1:3). P-value refers to Kolmogorov-Smirnov test or Chi-Square test for number of pregnancies.

Table 6.2 Quality of life results.

	Preoperative	Postoperative	p-value
EQ-5D-5L score	0.384(0.291:0.516)	0.735 (0.690:0.818)	0.008
EQ-5D-5L VAS	46 (35:61)	72 (58:85)	0.005

All values are median with interquartile range (1:3). P-value refers to Wilcoxon-Signed Ranks test.

Gait

Gait analysis revealed no differences in parameters between pre- and postoperative data. Postoperatively, step length and stride length were shorter as compared to matched controls. Walking speed was significantly slower in postoperative patients compared to matched controls. Other outcome

parameters were not different between postoperative patients and matched controls. Table 6.3 outlines the complete outcome data regarding gait.
In Additional File 6.1 the results of individual gait analysis are depicted in graphs. Although not statistically significant, a trend of improvement can be observed in these graphs. For example, it is noticeable that cadence and walking speeds increase, and double support phase and stride time decrease in most patients. When excluding the two main outliers (patient number 8 and 9) the improvement becomes more obvious (Additional File 6.2).

Table 6.3 Outcomes of gait analysis.

	Preoperative (1)	Postoperative(2)	Matched controls (3)	p-value
Cadence (steps/min)	101 (91:104)	106 (105:109)	116 (114:120)	1-2: 0.839 2-3: 0.054
Double support phase (s)	0.33 (0.30:0.35)	0.31 (0.25:0.39)	0.21 (0.19:0.21)	1-2: 0.480 2-3: 0.149
Single support phase (s)	0.44 (0.43:0.50)	0.43 (0.40:0.47)	0.41 (0.40:0.42)	1-2: 0.293 2-3: 0.254
Step length (m)	0.56 (0.53:0.59)	0.58 (0.57:59)	0.66 (0.64:0.71)	1-2: 0.941 2-3: 0.013*
Step time (s)	0.59 (0.58:0.66)	0.59 (0.58:0.66)	0.51 (0.50:0.53)	1-2: 0.423 2-3: 0.155
Step width (m)	0.15 (0.14:0.16)	0.17 (0.13:0.18)	0.12 (0.11:0.16)	1-2: 0.732 2-3: 0.286
Stride length (m)	1.11 (1.06:1.20)	1.16 (1.12:1.24)	1.32 (1.30:1.42)	1-2: 0.959 2-3: 0.012*
Stride time (s)	1.19 (1.15:1.32)	1.14 (1.11:1.15)	1.03 (1.00:1.05)	1-2: 0.432 2-3: 0.154
Walking speed (m/s)	0.96 (0.80:1.05)	1.01 (0.98:1.13)	1.33 (1.23:1.41)	1-2: 0.637 2-3: 0.009*

All values are medians with interquartile range (1:3). P-value refers to linear mixed model analyses.

Single leg stance

Postoperatively, patients reached a lower mean hip angle than matched controls. None of the study groups reached a hip angle of 90° over the task duration of 10 seconds, as was instructed. None of the parameters of interest improved following MISJF in the patients group. Table 6.4 outlines the complete outcome data regarding SLS.
Center of pressure and center of mass during SLS are depicted in stabilographs for all study groups (Figure 6.1). A statistically significant difference in sway in center of mass in medial-lateral range for left leg ($p<0.013$) was observed between study groups, in which postoperative patients approached matched control data.

Table 6.4 Outcomes of SLS.

	Preoperative (1)	Postoperative (2)	Matched controls (3)	p-value
Pelvic obliquity L (°)	10.1 (7.2:12.9)	7.6 (4.1:11.3)	9.5 (8.0:12.4)	1-2: 0.143 2-3: 0.216
Pelvic obliquity R (°)	11.5 (6.9:16.3)	10.6 (6.0:14.4)	7.9 (5.5:10.3)	1-2: 0.438 2-3: 0.237
Hip angle L (°)	76.9 (72.1:80.3)	75.4 (67.4:81.5)	84.2 (81.1:87.0)	1-2: 0.168 2-3: <0.001*
Hip angle R (°)	71.1 (67.8:75.9)	71.7 (62.3:77.3)	83.4 (79.4:86.9)	1-2: 0.132 2-3: <0.001*
Knee angle L (°)	17.7 (7.8:21.0)	15.8 (13.5:18.8)	13.8 (7.2:16.4)	1-2: 0.839 2-3: 0.179
Knee angle R (°)	15.1 (12.4:20.3)	15.6 (13.3:19.8)	14.8 (12.8:16.3)	1-2: 0.839 2-3: 0.445

All values are medians with interquartile range (1:3). P-value refers to linear mixed model analyses.

Sit-to-stance

Patients improved their total STS time after the operation by more than 1 second (Table 6.5). This difference was caused by improvements in the leaning phase. The momentum and extension phase remained unimproved and slower than matched controls.

Disbalance during STS, measured as the absolute difference in GRF between both legs, is visualized in Figure 6.2. GRF distribution showed improvement, but the change did not reach statistical significance.

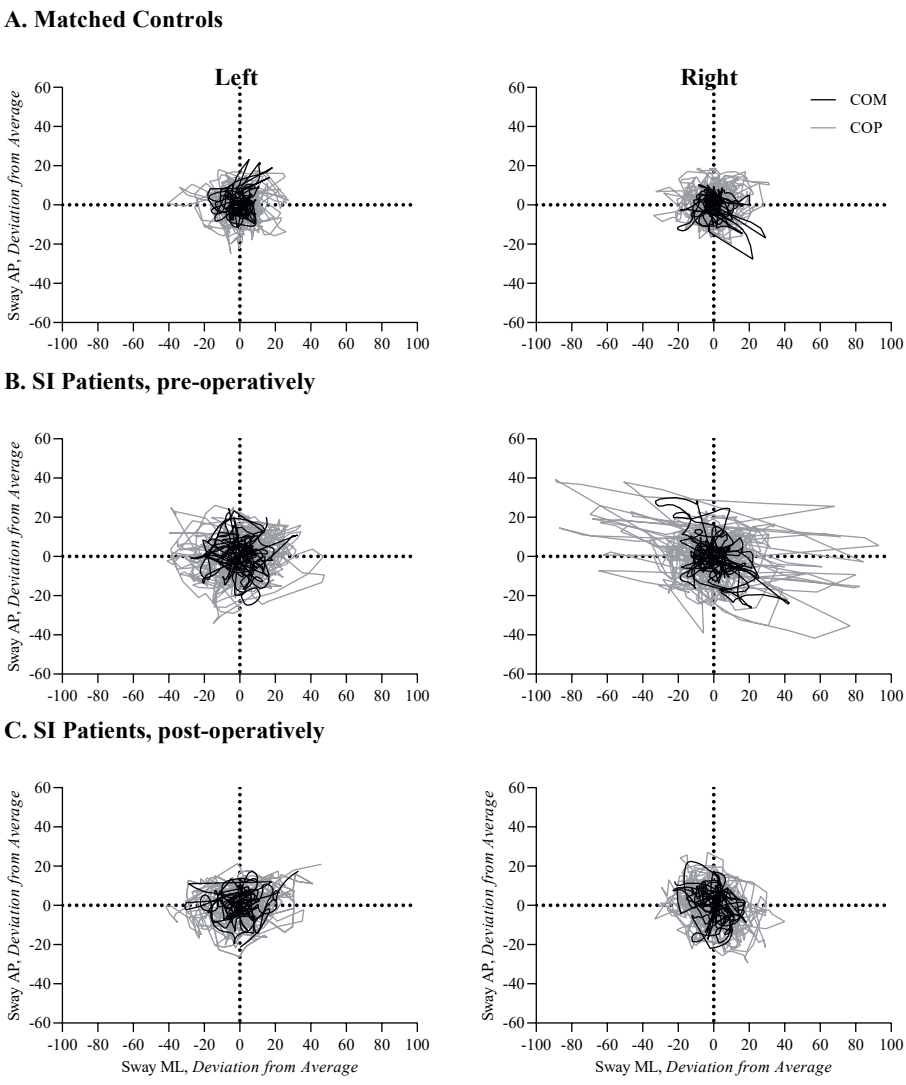

Figure 6.1 Stabilographs of study groups during SLS. COM: center of mass, COP: center of pressure right, AP: anterior-posterior, ML: medial-lateral.

Table 6.5 Outcomes of STS.

	Preoperative (1)	Postoperative (2)	Matched control group (3)	p-value
Leaning phase (s)	1.11 (0.97:1.31)	0.57 (0.39:0.75)	0.66 (0.58:0.78)	1-2: 0.031* 2-3: 0.134
Leaning (%)	31.2 (28.7:40.7)	27.6 (22.0:29.0)	35.9 (34.1:40.5)	1-2: 0.155 2-3: 0.002*
Momentum phase (s)	0.37 (0.30:0.56)	0.36 (0.32:0.41)	0.20 (0.17:0.25)	1-2: 0.605 2-3: 0.016*
Momentum (%)	11.3 (9.2:18.4)	18.0 (15.2:25.9)	9.8 (8.7:14.5)	1-2: 0.017 2-3: 0.011
Extension phase (s)	1.83 (1.70:2.37)	1.09 (0.71:1.39)	0.89 (0.84:1.01)	1-2: 0.077 2-3: 0.277
Extension (%)	51.6 (49.4:62.9)	56.6 (46.0:61.9)	50.8 (46.6:54.3)	1-2: 0.969 2-3: 0.217
Total STS time (s)	3.41 (3.11:4.57)	2.21 (1.74:2.50)	1.92 (1.69:1.99)	1-2: 0.037* 2-3: 0.269

All values are medians with interquartile range (1:3). P-value refers to linear mixed model analyses.

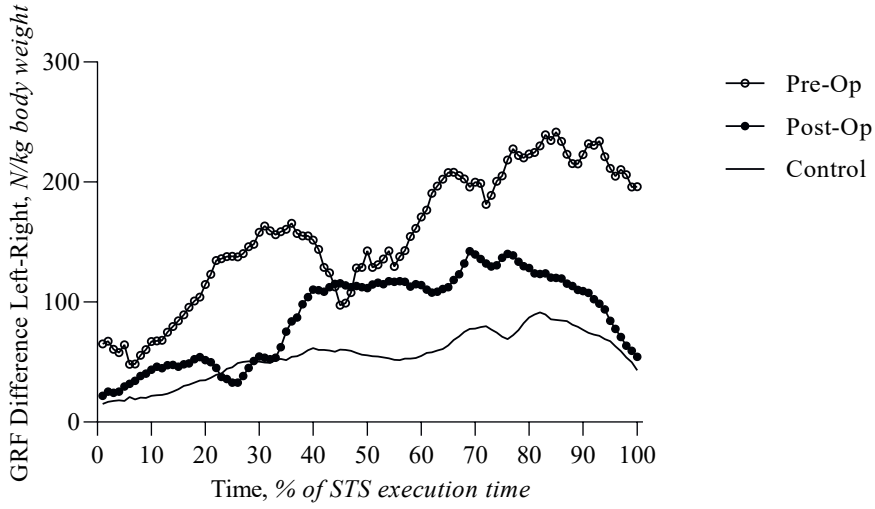

Figure 6.2 Absolute left-right difference in GRF during STS across study groups. Pre-op: preoperatively, Post-op: postoperatively, GRF: ground reaction force, N: newton, kg: kilogram, STS: sit-to-stance.

Discussion

Although the implementation of MISJF in SIJ dysfunction is still increasing and evidence for the effectiveness strengthens, controversy remains.[15,16] Current studies mainly focus on subjective outcome measures, such as pain, mobility

and quality of life through questionnaires.[17] To evaluate the effectiveness of MISJF using objective measures of mobility and function, objective outcome measures should be investigated in addition to patient-reported outcome measures. In this small cohort of postpartum SIJ dysfunction patients, quality of life improved significantly three months following MISJF. These improvements are comparable to current literature, in which 6 and 12 months follow-up is mostly implemented.[18,19] Although these subjective outcome measures are crucial in the assessment of the effects of MISJF, there is an increasing interest for objective outcome data. This study is one of the first to give insights in such data. Prior studies have evaluated the effect of pelvic belts on SIJ dysfunction and noted improvements in quality of life and postural steadiness during locomotion.[20,21] The main finding of the present study is comparable, as MISJF results in overall better task execution in patients with postpartum SIJ dysfunction in addition to an improved quality of life. Improvements are most apparent in dynamic balance during SLS and STS execution time. The results of this study therefore strengthen the evidence of effectiveness for MISJF in SIJ dysfunction.

In gait analysis, most parameters improved postoperatively compared to preoperatively, however no statistical significance was reached. In our previously published feasibility study, we noted that nearly all parameters (e.g. cadence, double support phase, walking speed) were statistically significantly different between preoperative patients and matched controls during gait. These differences are not found in the current study, indicating that postoperative patients show a more natural gait, comparable to healthy individuals. The data in Additional Files 6.1 and 6.2 confirm the latter, as individual data mostly shows improvements in gait parameters. Walking speed is one of the parameters that universally increases when looking at Additional File 6.2. An increased walking speed may indicate less back pain or referred leg pain postoperatively, as we know patients that suffer from those complaints walk slower.[22]

No improvement in joint angle was observed in the performance of a SLS following MISJF. Although mean hip angle was statistically significantly lower in postoperative patients compared to matched controls, none of the study groups reached a mean hip angle of 90°, as was instructed. This was also the case in our preoperative motion analysis paper, where we also investigated motion patterns in healthy students.[12] These data thus suggest that performing a SLS with a hip angle of the risen leg of 90° for 10 seconds is a challenging task, even among healthy individuals. A potential explanation of a decreased hip

angle in postoperative patients might be surgically induced gluteal damage, in which strength still needs to be fully restored three months following surgery.[23] This is one of the reasons we recommend physical therapy programs following MISJF to largely focus on strengthening gluteal muscles. Potentially, measuring the effects of MISJF and supplementary physical therapy three months postoperatively, in a challenging task like SLS, might be too soon to expect improvement. Altered function of the gluteus musculature has been found in patients with SIJ dysfunction.[24] Consequently, differences in pelvic obliquity are expected between study groups, as gluteal function is heavily involved in pelvic obliquity. However, in both our studies concerning motion analysis in SIJ dysfunction, we found no differences in pelvic obliquity angle. Perhaps, pelvic obliquity movement is too small to measure significant differences across study groups. Further differences in SLS task execution (e.g. different mean hip angle) also influence the requirement of pelvic obliquity, subsequently making it more difficult to assess differences. Although the parameters of joint angles did not improve following MISJF, stabilographs in Figure 6.1 indicate balance improvements in patients after surgery, as the sway decreases compared to preoperatively. This is not only visually apparent, but also present in statistical analysis for center of mass in medial-lateral range for left leg.

Total time to perform an STS improved in patients following MISJF and was comparable to that of matched controls. Most improvement was reached in the leaning phase, which was even faster in postoperative patients than in matched controls. Patients with SIJ dysfunction often describe pain by getting up of a chair.[2] The improved total time to perform an STS might therefore indicate that the task is less painful following MISJF. In terms of force distribution, Figure 6.2 indicates notable, yet statistically unsignificant differences in GRF between both legs during STS across study groups. GRF differences decrease in postoperative patients compared to preoperatively and are more in line with that of matched controls. This indicates that the load capacity is more evenly distributed across both legs. A potential explanation might be that postoperative patients experience less complaints in their SIJ and are therefore less occupied with relieving their (most) symptomatic leg.

Limitations

A limitation of the current study is the small sample size. We previously performed a feasibility study with the same patient group as in the current study. In this feasibility study we were able to measure statistically significant differences in motion patterns between patients with postpartum SIJ

dysfunction and matched controls. Therefore, we performed similar analyses in the same group following MISJF, to evaluate the effects of this intervention. Although several significant differences were observed, for other parameters larger sample sizes may be needed to overcome intra- and inter-individual variability. Frequently observed trends in the present data support the need for larger samples. Larger sample sized studies may also identify which individual patients benefit more from MISJF in terms of improvement in motion patterns. Another limitation to the current study is the short follow-up period. Three months postoperatively might be too early to expect large improvements in motion analyses. In a large number of patients bilateral SIJ complaints are present, for which a second surgery is needed, where the contralateral SIJ is fused to further alleviate complaints. In these patients further improvement can still be expected following second surgery.

Conclusion

This study suggests that motion patterns improve in patients with postpartum SIJ dysfunction three months following MISJF. Most notable differences were an improved balance during SLS and a faster STS performance. Additional studies with longer follow-up and larger sample sizes should provide more detailed insights on motion analysis in patients with postpartum SIJ dysfunction following MISJF.

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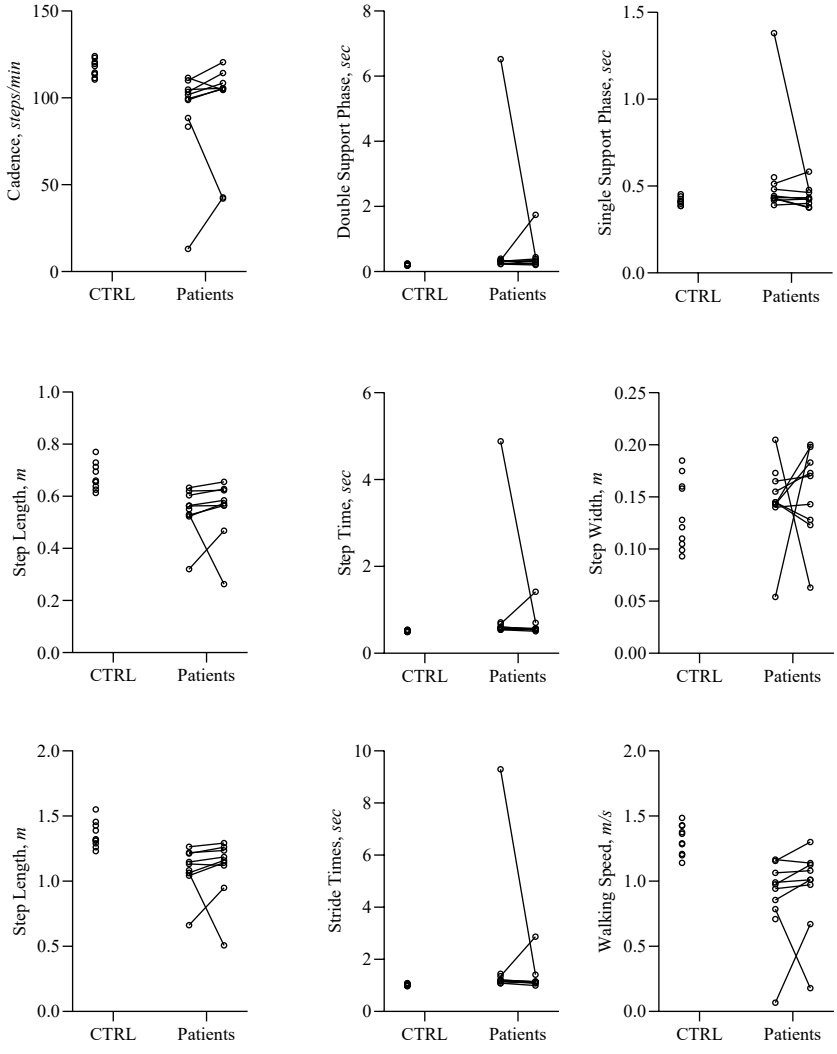
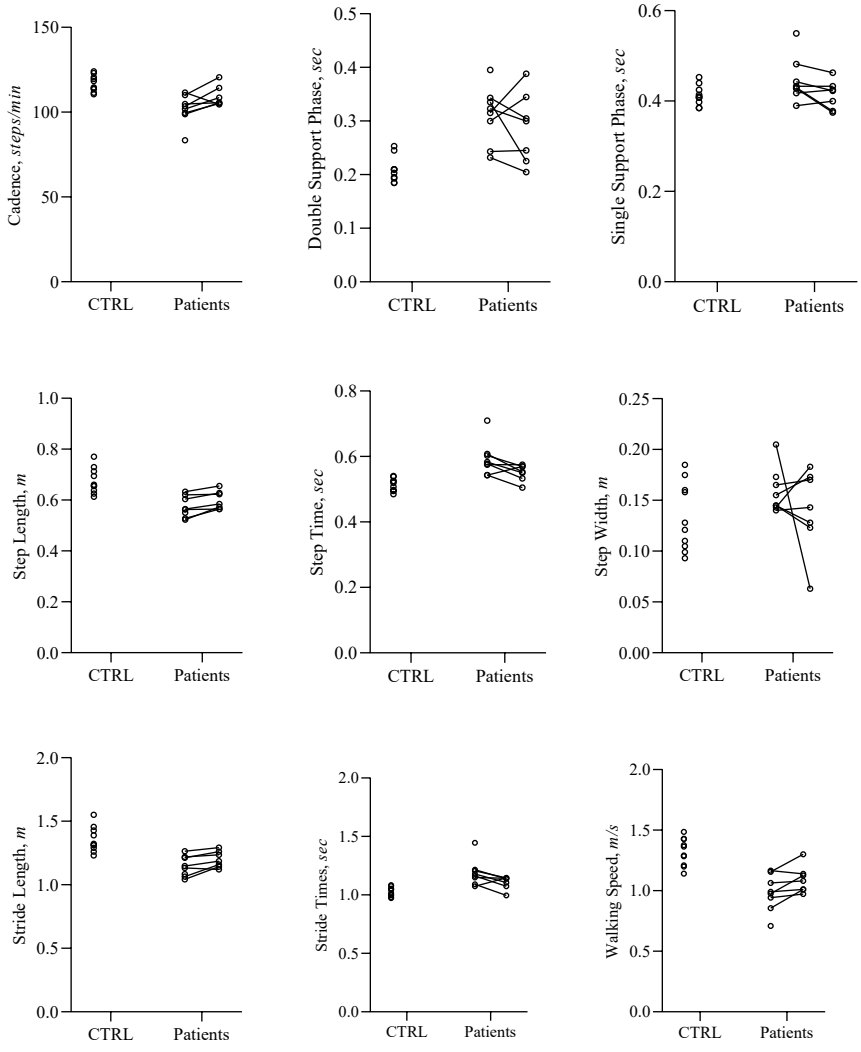
Appendix 6.1

Additional File 6.1: Individual parameter outcome of subjects during gait

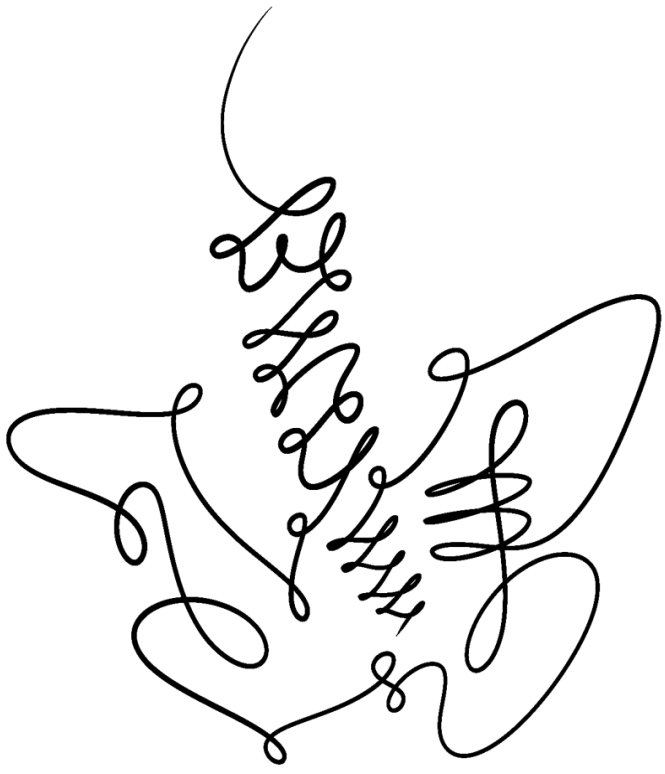


CTRL: matched controls

Additional file 6.2: Individual parameter outcome of subjects during gait, with exclusions of outliers (#8 and 9)



CTRL: matched controls



Chapter 7

A protocol for a multicenter randomized controlled trial for the effectiveness of minimally invasive sacroiliac joint fusion compared to prolonged conservative therapy in sacroiliac joint dysfunction: The SACRIFICE study

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In preparation

Abstract

Introduction
Sacroiliac joint (SIJ) dysfunction is a common reason for chronic low back pain. Treatment strategies for SIJ dysfunction include non-surgical therapies and surgical treatment. Non-surgical therapies have limited effectiveness when it comes to sustainability. In terms of surgical treatment, minimally invasive sacroiliac joint fusion (MISJF) is a procedure that is described more often for SIJ dysfunction. Studies comparing MISJF and conservative treatment are in favor of MISJF in terms of pain reduction and improvement of mobility, but are not yet convincing to justify incorporation into medical guidelines, as these are industry funded and limited in study design. Literature on cost-effectiveness in MISJF is even more scarce and lacks consideration of societal costs. We therefore aim to perform the first independent randomized controlled trial (RCT) of MISJF vs prolonged, standardized, conservative treatment with a comprehensive assessment of clinical and economic effects.

Methods and analysis
This is a nationwide, prospective, multicenter RCT. All included patients diagnosed with SIJ dysfunction will be randomized to either prolonged standardized conservative treatment or operative treatment (within 4 to 6 weeks). Patients in the conservative group may undergo MISJF earliest after 6 months. Outcome measurements will be performed before randomization and 3, 6, 12 and 24 months after initiation of treatment. The primary outcome is back function. Secondary outcome measures include cost-effectiveness from a healthcare and societal perspective.

Strengths and limitations of this study

- The proposed study design, an independent prospective randomized controlled trial with a broad economic analysis, will investigate the cost-effectiveness of MISJF and prolonged, standardized, conservative treatment for SIJ dysfunction, resulting in level I evidence.
- This study will lead to revised guidelines in the treatment of patients with SIJ dysfunction.
- Sample size calculation acknowledges the number of patients that will receive MISJF after 6 months of conservative treatment.
- This study lacks blinding of study groups, potentially increasing bias due to the knowledge of which intervention is being received by patients.
- External validity and generalizability are limited, as costs are country specific.

Introduction

Chronic low back and buttock pain is a frequent complaint in the general population. The sacroiliac joint (SIJ) is involved in 14-22% of all patients presenting with this pain.[1,2] SIJ dysfunction is relevant in patients with axial spondylitis, but can also occur posttraumatic, post-partum, or in a degenerative condition. Connective tissue disorders, such as Ehlers Danlos Syndrome (EDS) and prior lumbar fusion surgery are also a prevalent risk factor for the development of SIJ dysfunction.[3,4] Quality of life in patients with SIJ dysfunction is low and comparable to other orthopaedic conditions, such as hip and knee osteoarthritis.[5]

Treatment strategies for SIJ dysfunction include non-surgical therapies and surgical treatment. Non-surgical therapies, such as oral analgesic use, physical therapy, radiofrequency denervation and intraarticular steroid injections, have limited effectiveness when it comes to sustainability.[6–10] Although physiotherapy interventions can be effective in reducing pain and disability at first, complaints often return. Furthermore, for many patients reduction of complaints achieved through physical therapy is insufficient.[11] Return of pain 6 to 12 months following intra-articular steroid injections or radiofrequency denervation is also common.[12] In terms of surgical treatment, minimally invasive sacroiliac joint fusion (MISJF) is a procedure that is described more often for SIJ dysfunction. The initial outcomes of MISJF are promising in terms of pain reduction and improvement of mobility.[13] However, there are still controversies regarding surgical treatment in SIJ dysfunction, mostly concerning its efficacy variability and generalizability. Literature comparing MISJF with conservative treatment is minimal and most studies are industry-funded.[14,15] As we concluded in our systematic review and meta-analysis significant more data are required from well-powered, independent, randomized controlled trials (RCT) with validated outcome measurements to justify MISJF as recognized standard surgical indication.[16] The aim of this RCT is to evaluate the clinical and cost-effectiveness of MISJF compared to prolonged standardized conservative treatment in patient with SIJ dysfunction with regard to reduction of pain and disability.

Materials and methods

Study design

Figure 7.1 depicts the flowchart of the study process. This is a nationwide, prospective, multicenter RCT. All included patients diagnosed with SIJ dysfunction (using at least 50% VAS-pain reduction after diagnostic SIJ intraarticular injection) will be randomized to either prolonged standardized conservative treatment or operative treatment (within 4 to 6 weeks). Patients in the conservative group may undergo MISJF earliest after 6 months. Outcome measurements will be performed before randomization and 3, 6, 12 and 24 months after initiation of treatment (for the conservative group, that is immediately; for the operated group, that is after surgery).

SIJ dysfunction is a relatively unknown clinical entity. To date most patients with chronic SIJ dysfunction are referred to a rehabilitation centre and only a limited number of hospitals is offering surgical treatment for this problem. By collaborating with dedicated rehabilitation clinicians and almost all Dutch hospitals where MISJF is performed, included patients will reflect a representative population treated for SIJ dysfunction in the Netherlands. All rehabilitation clinicians involved will be informed about this study. All patients presenting at the rehabilitation clinicians with SIJ dysfunction will be referred to the orthopaedic outpatient clinic of one of the participating hospital centres. After confirmation of the diagnosis, through a positive response to intraarticular SIJ injection (50% VAS-pain reduction), the patient is eligible for randomization. When eligible, the researchers will inform the patient, and when they are willing to participate, include them. The patient will be randomized either in de MISJF group or in the prolonged conservative treatment group. Surgery will be carried out according to the current guidelines in all participating centres. Surgery is performed within 4 to 6 weeks after randomization. Conservative treatment is carried out by one of the dedicated rehabilitation clinicians and 6 months after allocation to the conservative treatment arm, it is allowed to undergo MISJF, in case of failed conservative treatment. The study inclusion will be approximately 2 years, and the follow-up period 2 years (total study duration 4 years). Surgical treatment is always by a dedicated orthopaedic or general surgeon, who has experience with MISJF. Besides studying the treatment groups, Informal Care Givers (ICG) will be studied, by asking them to complete 3 questionnaires during 6 months follow-up, considering quality of life.

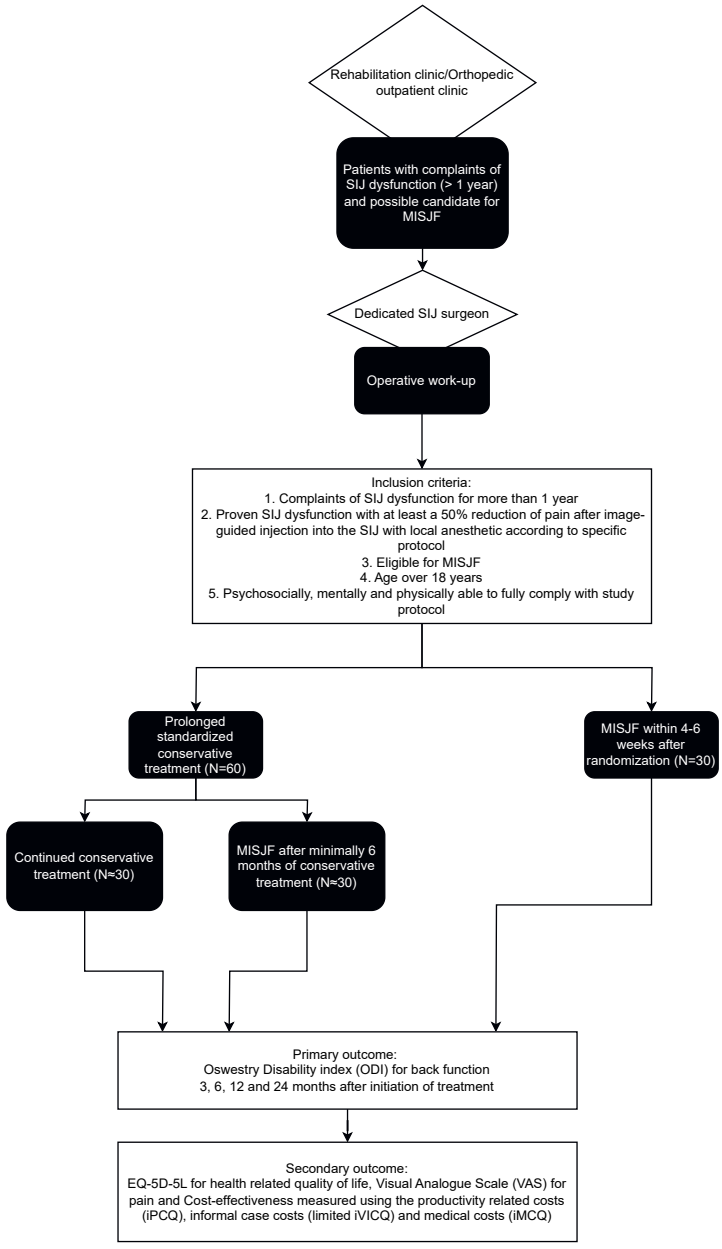

Figure 7.1 Flowchart of study process.

Patient and public involvements

First, multiple meetings with the board of the Ehlers-Danlos Syndrome (EDS) Society were conducted, a patient organization with many SIJ dysfunction patients, to discuss the protocol and patient information. Second, panel discussions with patients, who underwent MISJF in the Netherlands were conducted to better understand their experiences and to assess feasibility, specifically the chance of being randomized into the prolonged conservative treatment group.
The EDS society board and patients will continue their involvement through meetings with the investigators, and through participation in development of the implementation strategy.
Third, semi-structured face-to-face interviews will be conducted 3 months after treatment. This process evaluation assesses the implementation and sustainability of MISJF.

Participants and recruitment

Adult patients with prolonged complaints of SIJ dysfunction for more than 1 year presenting at the rehabilitation clinician or orthopedic outpatient clinic and who are eligible for MISJF are potentially eligible to participate in this study. Indication for MISJF is based on medical interviewing, medical examination including the following SIJ provocative tests; flexion abduction external rotation (FABER-test), thigh thrust, Gaenslen's test, sacral distraction, lateral compression, and sacral thrust and an image-guided intra-articular SIJ injection with local anesthetic according to a specific guideline.[17,18] At least 3 provocative tests should evoke SIJ pain and at least a 50% reduction of SIJ pain 30 to 60 minutes following image-guided injection should occur to be eligible for MISJF.

Inclusion criteria

In order to be eligible to participate in this study, a subject must meet all of the following criteria:

1. Complaints of SIJ dysfunction for more than 1 year.
2. Proven SIJ dysfunction with at least a 50% decrease of pain after image-guided injection into the SIJ with local anesthetic according to specific guideline.
3. Eligible for MISJF surgery.
4. Age over 18 years.

5. Psychosocially, mentally, and physically able to fully comply with this study protocol.
6. Informed consent prior to this study.

In order for ICG to be eligible to participate, a subject must meet all of the following criteria: The patient where the ICG offers his care has to participate in the SACRIFICIE-study:
1. Age over 18 years
2. Psychosocially, mentally and physically able to fully comply with this study protocol.
3. Informed consent prior to this study.

Exclusion criteria

A potential subject who meets any of the following criteria will be excluded from participation in this study:
1. Complaints of SIJ dysfunction for less than 1 year.
2. Previous SIJ surgery.
3. Inadequate command of the Dutch language.
4. Ineligible for MSIJF surgery.

A potential ICG who meets any of the following criteria will be excluded from participation in the study:
1. Inadequate command of the Dutch Language.

Outcome measures

Primary outcome measure

- The primary outcome is Oswestry Disability Index (ODI) for back function.

Secondary outcome measures

- Cost-effectiveness measured using the productivity related costs (iPCQ), informal care costs (limited iVICQ), medical costs (iMCQ) and the health-related quality of life, assessed as EQ-5D-5L-index.
- Visual analog scale (VAS) for pain.
- Change in Care-related Quality of Life (measured with CarerQol-7D, SRB) pre- and postoperatively for the MISJF group.

- Complications, as a result of surgery in the MISJF group, are defined as: implant malposition (potentially causing persistent radicular pain because of nerve root impingement), postoperative infection, deep venous thrombosis, hematoma, hardware failure, neurological deficits and other complications as pneumonia or urinary tract infection.
- Percentage of patients undergoing MISJF after prolonged standardized conservative treatment.

Process evaluation will be performed according to the framework provided by Saunders.[19] Interviews will be held with randomly chosen patients and ICG, and the principal investigator of each participating centre to collect qualitative data.

Other study outcome measures

Other study parameters are sex, age, BMI, smoking habits, occurrence of diabetes, diagnosis and ASA classification. Also, perioperative morbidity, assessed with duration of surgery, intraoperative blood loss and duration of hospitalization.

Randomization

Participants will be randomly assigned by the researcher to either the MISJF group or prolonged standardized conservative therapy group with a 1:2 allocation using a web-based computer-generated randomisation schedule stratified by treatment hospital by variable block algorithm with random blocks of 4, 6 or 8. The statistician is blinded for the allocated treatment.
The ICG will be linked to the specific patient where he/she is taking care of.

Sample size calculation

In the only study with available data of patients successfully treated conservatively for 12 months, Polly et al. report improvements in ODI by 14.1 in the conservative group, and 29.3±19.9 in the MISJF group.[20] This expected difference has been shown to be clinically meaningful.[21,22] Using these data, and a power of 80%, the required sample size is 27 per group. Accounting for 10% loss-to-follow-up, we will include 30 patients per group. In the present study, we assume 50% crossover based on the study of Dengler with 43% cross-over.[14] Two other studies reported 89% crossover, however these were USA studies, opposed to the European study of Dengler et al. This difference may be explained by differences in access to surgery, and conservative treatment may

explain different preferences or access to treatment. Crossover exceeding 50% would demonstrate the failure of conservative treatment and imply superiority of surgical treatment. From this perspective, a meta-analysis of available studies (Cher 2016) revealed treatment failures (defined as insufficient reduction in ODI) was 90% in conservative management, and 28% in operative treatment. Using these proportions, a sample of 14 patients (99% power) would suffice to indicate statistically significant ($p<0.05$) differences between groups.[23]

Statistical analysis

Frequency tables will be provided for all categorical demographic information. Continuous variables will be presented as mean ± standard deviation (SD) or median ± interquartile range (IQR) depending on the distribution of the data. Analysis will be performed by principal investigators using IBM SPSS statistical software package version 27 (SPSS Inc., Chicago, IL). Missing values will be imputed using stochastic regression imputation using full conditional specification. Group differences will be determined over time (i.e. the slopes of the relation between time and ODI/EQ-5D-5L/VAS by means of logistic regression analysis. Difference in change from baseline for fixed time points will be determined by using linear mixed models. Effect sizes and their 95% confidence intervals will be estimated. A two-sided significance level of 0.05 will be used as a threshold to determine whether differences are statistically significant.

Economic evaluation will be conducted as cost-effectiveness analysis (CEA) and cost-utility analysis (CUA), with remission defined as a 16% change in disability measured with ODI and quality-adjusted life years (QALYs) as outcomes. Also, a budget impact analysis (BIA) will be conducted to assess how health care budgets are changed when the intervention is offered to 10, 30 and 50% of the target group, and for the extreme scenario in which 100% of the target group will be receiving the intervention. The BIA will be conducted from various perspectives: (1) wider societal perspective, i.e. including productivity losses; (2) a narrower perspective of the public purse (in Dutch: Budgettair Kader Zorg); (3) the perspective of the health care insurer. All scenarios will be compared with a base-case scenario, reflecting care as usual.

Treatment of subjects

MISJF group

Minimally invasive sacroiliac joint fusion will be performed as standard care. The patient is placed in prone position. Intraoperative fluoroscopy is used during surgery for optimal placement of implants. After anesthesia is administered the patient is prepped in sterile fashion. Pelvic inlet and outlet views are utilized to obtain an appropriate starting point. A 3cm lateral incision is made across the sacral midline. A guide pin is placed across the ilium and across the SIJ. A drill is used to create a pathway and decorticate the bone. A triangular broach is then used to further decorticate the bone and prepare the pathway to receive the first implant. This implant is mostly seated within the sacral ala. The second implant is generally located above or adjacent to the S1 foramen and the third between the S1 and S2 foramen. Because of anatomical differences between patients, position of implants may differ slightly. The incision is then irrigated with bupivacaine and the tissue layers are sequentially closed.

Prolonged standardized conservative treatment group

Conservative therapy is in line with existing Dutch practices and directed by one of the rehabilitation clinicians for each patient. According to each subject's individual needs the best suitable therapy will be selected. Therapy may include pain medications, physical therapy following Dutch guidelines and intraarticular SIJ steroid injections. A holistic approach will be considered, including psychological problems. In case conservative treatment fails after 6 months (according to the patient) following the start of the study, patient is allowed to undergo MISJF surgery.

Ethics and dissemination

Ethical approval will be applied for from the Medical Ethical Committee Zuyderland, Heerlen, the Netherlands. Informed consent will be obtained in writing from all participants prior to study enrollment. Study results will be disseminated through presentation at a peer-reviewed medical journal. We also plan to present our study results at selected conferences and scientific meetings.

Discussion

There is currently no consensus on when surgery is indicated in patients with SIJ dysfunction. Naturally, surgical intervention for disabling symptoms attributable to the SIJ should be considered if pain is refractory to conservative treatment. Despite increasing evidence of effectiveness, controversy remains, and physicians often restrain from this extensive treatment. One reason may be that getting an accurate diagnosis can be elusive. Another may be that previous open surgery for SIJ pain was not appealing and often not effective in adequately reducing complaints. Currently, several minimally invasive systems are available to achieve MISJF. To date, most published studies describe the use of cannulated triangular, titanium implants with reasonable results when it comes to pain, disability and quality of life.[13] The current evidence is not yet convincing to justify incorporation into medical guidelines. Most studies are industry-funded, introducing a potential risk of bias in the reporting of results, and delayed surgery in the initially conservatively treated patients has been insufficiently considered in study design.[14,25] In terms of cost-effectiveness, one study concluded MISJF to be cost-effective after 13 years versus conservative treatment.[23] However, this study is also industry-funded and lacks consideration of societal costs. Societal costs are important to take into account in this group of patients, as most of them are young female patients who are in labor force. Costs associated with absenteeism may be substantial for this health problem.

There are some limitations to our study protocol that should be mentioned. Because of the nature of this study, it lacks blinding of study groups. Potentially increasing bias due to the knowledge of which intervention is being received by patients. This might be especially relevant in our study as a large group of potential subjects have been through an extensive conservative trajectory before considering surgical intervention. Getting assigned in the conservative treatment group might be discouraging for these patients. However, patients should consider this as a last chance to refrain from surgical intervention, as we believe extensive standardized conservative treatment directed by dedicated rehabilitation physicians is the best non-surgical treatment option available. This is also one of the aspects in which our study is different from current RCT's comparing conservative therapy with MISJF, where conservative therapy is directed by the site investigator and therapy consists of continuing physical therapy.[14,25] Also, in this study a holistic approach will be considered, including psychological problems when appropriate. External validity is another limitation of this study, as costs are country-specific. For instance, costs of

absenteeism are dependent on country, different salaries, and duration. The costs of surgical intervention and hospital admission is also different between countries. Nevertheless, we expect that the proportion of costs and effectiveness can be extrapolated to other countries, even though exact costs cannot.

We therefore aim to perform the first independent RCT of MISJF vs prolonged, standardized, conservative treatment with a comprehensive assessment of clinical and economic effects. Per confirmed hypothesis, MISJF can be presented to patients and colleagues as evidence-based treatment. Current skepticism due to sponsorship bias can be disproved. Thereby, MISJF can be incorporated into medical guidelines as valuable alternative. Currently MISJF is reimbursed, yet stronger evidence is required for continuation of reimbursement. If our hypothesis is not confirmed, costly MISJF procedures can be avoided, while parallelly, we will seek responder/non-responder analyses to (in)validate current clinical experience.

The Dutch Spine Society supports the intentions of the study. The first step is to revise the national guidelines if the proposed study shows greater (cost-)effectiveness of MISJF compared to conservative treatment. MISJF can then be implemented, leading to standard and continues reimbursement. The process evaluation in this study will offer valuable insight into the optimal process surrounding MISJF.

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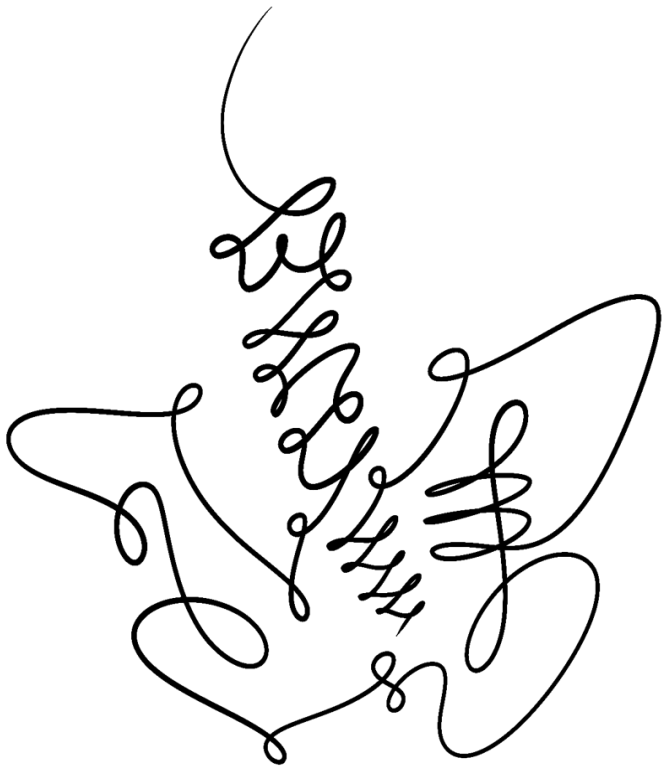

Chapter 8

A Randomized controlled Trial on the Effect of local analgesia for pain relief after Minimally Invasive Sacroiliac joint fusion: The ARTEMIS study

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Submitted

Abstract

Introduction
During the first postoperative days following minimally invasive sacroiliac joint fusion (MISJF), patients often report serious pain, which contributes to high utilization of painkillers and prevention of early mobilization. The aim of this study is to investigate the effectiveness of intraoperative sacroiliac joint (SIJ) infiltration with analgesia in reducing postoperative pain after MISJF.

Methods
This prospective, double-blind randomized controlled trial investigates the effectiveness of intraoperative SIJ infiltration with bupivacaine 0.50% versus placebo (NaCl 0.9%) in 42 patients in reducing postoperative pain after MISJF. The primary outcome was difference in pain between bupivacaine and placebo groups, assessed as fixed factor in a linear mixed model. Secondary outcomes were opioid consumption, patient satisfaction, adverse events, and length of hospital stay.

Results
SIJ infiltration with bupivacaine did not affect postoperative pain scores in comparison with placebo, neither as group-effect (p=0.68), nor dependent on time (group*time: p=0.87). None of the secondary outcome parameters were affected in the postoperative period in comparison with placebo, including opioid consumption (p=0.81).

Conclusion
Intra-articular infiltration of the SIJ with bupivacaine at the end of MISJF surgery is not effective in reducing postoperative pain. Hence, we do not recommend routine use of intraoperative SIJ infiltration with analgesia in MISJF.

Introduction

Chronic low back pain is often caused by a dysfunctional sacroiliac joint (SIJ), but frequently overlooked, potentially due to difficult diagnosis and inadequate treatment options.[1,2] If pain allocated to SIJ is refractory to conservative treatment options, minimally invasive sacroiliac joint fusion (MISJF) is being considered.[3,4] This treatment option is supported by industry-sponsored studies reporting high satisfaction rates in MISJF-treated patients.[5] During MISJF, the SIJ is stabilized by percutaneously inserted implants.[6] The implants are inserted laterally through the gluteal musculature, and across the SIJ to achieve joint fusion. During the first postoperative days, patients often report pain in the operated area, and it is reasonable to assume that pain is induced upon loading this operated joint. This postoperative pain is difficult to manage adequately and prevents early mobilization.[7] This pain contributes to patients taking high doses of analgesics.[7,8] However, analgesics, especially opioids, can cause nausea and drowsiness, resulting in inability to mobilize adequately.[9] Combined, postoperative pain and nausea may extend hospitalization and cause negative experience of hospitalization.[10]

To reduce postoperative pain following MISJF, an intra-articular SIJ infiltration with analgesia at the end of the procedure is advocated. In several orthopedic procedures, for example total knee arthroplasty and spinal fusion surgery intraoperative infiltration of the wound bed results in decreased consumption of opioids, earlier mobilization and shorter hospitalization time.[11–13] However, the effects of such an infiltration in MISJF are unclear and have never been described. Infiltrating the SIJ only takes little extra operating time and a minimal amount of fluoroscopy screening time but may have significant impact on postoperative care.

The aim of this study is to determine whether intraoperative intra-articular analgesia with bupivacaine 0.50% is superior to placebo (intraoperative intra-articular infiltration of NaCl 0.9%) in reducing postoperative pain in patients after MISJF and to determine whether opioid use is reduced in the intervention group during the first 48 hours after surgery.

Methods

Study design

We conducted a prospective, double-blind, multi-center randomized controlled trial (blinding for the patient, clinician, and statistician) to investigate the effect of intraoperative SIJ infiltration with 1.5-5cc bupivacaine 0.50% on postoperative pain after MISJF compared with 1.5-5cc saline. Bupivacaine 0.50% was chosen for the intervention group because it is often used in diagnostic injections of the SIJ, with or without anti-inflammatory steroids, and it is effective in reducing pain in patients suffering from SIJ dysfunction.[14–16] Randomization was block-wise and stratified by center. This trial was registered at the Netherlands trial register (NL9151, 29/12/2022). The detailed study protocol has been published previously.[17] The study protocol was written in accordance with the Consolidated Standards of Reporting Trials (CONSORT) 2010 checklist of information to include when reporting a randomized trial.[18] This study has been approved by the Medical Ethical Committee (METCZ 20210069) at both participating centers (Zuyderland Medisch Centrum, Sittard-Geleen, and Medical Spectrum Twente, Enschede, both the Netherlands). The study was carried out in accordance with the protocol and with the principles enunciated in the current version of the Declaration of Helsinki, in accordance with the Medical Research Involving Human Subjects Act (WMO) and the guidelines of Good Clinical Practice (GCP). All subjects were informed on the purpose of the study and gave written informed consent before participation.

Study population

Adult patients referred to two spinal orthopedic outpatient clinics eligible for primary MISJF surgery were potentially eligible to participate in this study. Indication for MISJF was considered by suspicion of SIJ pain based on medical interviewing, excluding other causes, and medical examination included provocative tests of which 3 had to evoke SIJ pain. In case of suspicion of SIJ dysfunction, diagnosis was confirmed by the gold standard image-guided intra-articular SIJ injection with local anesthetic according to the specific guideline. Patients were only eligible for MISJF if at least a 50% reduction of SIJ pain 30 to 60 minutes following image-guided injection occurred. Patients with previous ipsilateral surgery of any kind were not included in this study. Previous contralateral surgery of the SIJ was not an exclusion criterion.

Interventions

MISJF was performed under general anaesthesia in prone position. Short-acting opioids like sufentanil or fentanyl were used during surgery. To prevent the influence of long-acting opioids on the postoperative pain and therefore obscuring the result of SIJ infiltration, no long-acting opioids were administered during or at the end of surgery. Depending on the local anatomy, two or preferably three triangular implants were placed across the SIJ with fluoroscopy, according to manufacturer's instructions. After wound closure, a spinal needle was used to infiltrate the SIJ intra-articularly under fluoroscopic guidance. The distal part of the SIJ was visualized using fluoroscopy in anterior-posterior view applying lateral tilt as needed for optimization. Needle position was checked, and images were stored for potential review. Either bupivacaine 0.50% 1.5-5cc (intervention) or NaCl 0.9% 1.5-5cc (placebo) was infiltrated. Both groups received the same perioperative protocol, including preoperative cefazolin, postoperative analgesia consisting of acetaminophen 4 times 1000mg daily, standard physical therapy during hospitalization and deep venous thrombosis prophylaxis. Postoperatively, patients were transported to the recovery room, where they were monitored for a least one hour. During their stay at the recovery room and at the ward, patients received intravenous or intramuscular piritramide until the visual analogue scale (VAS) pain was ≤3. Dosage is determined based on visual analogue scale (VAS) pain score and body weight, 0.2-0.3mg/kg with a maximum of 80mg/day in four dosages.

Outcomes

The primary outcome was difference in pain, assessed using VAS between bupivacaine and placebo group during the first 48h after surgery, with repeated post-infiltration measurements at recovery entry, recovery exit, and after 2, 4, 6, 24 and 48 hours. Secondary outcome measures were opioid consumption, in which all opioid consumption is converted to morphine per os equivalent using a conversion table (Additional file 8.1), patient self-reported recovery using the General Surgery Recovery Index (GSRI) and VAS for satisfaction, leg and back pain, adverse events and length of hospital stay.[19] Other study parameters are sex, age, BMI, preoperative opioid usage, occurrence of diabetes, causes of SIJ dysfunction, previous pelvic or back surgery, pre-operative pain and patients physical condition (ASA classification). The amount of fluid that the surgeon was able to infiltrate in the SIJ, duration of surgery, intraoperative blood loss and intraoperative opioid administration were monitored.

Statistical analysis

Difference in pain between SIJ infiltration with 1.5-5cc bupivacaine 0.50% and placebo at around 2 hours after infiltration is the primary endpoint and was used to calculate the sample size. Based on our own preliminary data, derived from recovery unit charts, we estimated that the standard deviation of the pain score is 2.2. A two-point difference on the eleven-points (0 to 10) pain score is considered clinically relevant.[19,20] In order to obtain this clinically meaningful effect with 80% power, 19 patients are required per group. Because no contrast is implemented during infiltration, there is an estimated chance of 10% that the infiltration will not be administered intra- but peri-articular. However, the analgesic effect of intra- and peri-articular infiltration is similar.[21,22] When taking into account a 10% loss to follow-up, 42 patients (21 patients per group) were enrolled in this study.

Frequency tables were provided for all categorical demographic information. Continuous variables were presented as mean ± standard deviation (SD) or median ± interquartile range (IQR) depending on the distribution of the data. Analysis was performed by principal investigators using IBM SPSS statistical software package version 27 (SPSS Inc., Chicago, IL). Data was tested for normal distribution. When data was normally distributed a paired t-test was used to determine statistical difference between groups (e.g. pain score, cumulative opioid use). In case of absence for normal distribution, Wilcoxon Signed-Rank test was used. In addition, the group differences over time were determined using a linear mixed-effects model with group, time and the group-time interaction as fixed factors. Study center was included as random variable. Categorical data was assessed using Pearson's Chi-Square test and Fisher's exact test. A p-value ≤ 0.05 was considered statistically significant.

Results

Baseline characteristics

Patients' characteristics are described in Table 8.1. A total of 42 patients were included in this RCT. One patient was excluded from analysis because intraoperative infiltration of study medication was unsuccessful. The remaining patients received the per protocol allocated treatment and received the full 5cc of fluid infiltration. Twenty-two patients were analyzed to the bupivacaine group and nineteen patients to the placebo group.

Table 8.1 Characteristics of included patients between intervention and control group.

Variable	Bupivacaine (N=22)	Placebo (N=19)
Age in years, mean (SD)	47 (15)	47 (12)
Sex, (% (N) female)	77.3 (17)	94.7 (18)
Body-Mass-Index, mean (SD) $kg.m^{-2}$	27.9 (6.7)	28.6 (6.9)
Diabetes (% (N) yes)	4.5 (1)	5.3 (1)
Smoking (% (N) yes)	28.6 (6)	26.3 (5)
Preoperative opioids (% (N) yes)	36.4 (8)	36.8 (7)
Oral anticoagulation (% (N) yes)	22.7 (5)	10.5 (2)
ASA classification (% (N))		
I	9.1 (2)	10.5 (2)
II	63.6 (14)	73.7 (14)
III	27.3 (6)	15.8 (3)
Causes of SIJ dysfunction (% (N))		
Postpartum	36.4 (8)	47.4 (9)
Ehlers Danlos Syndrome	27.3 (6)	26.3 (5)
Prior lumbar fusion surgery	9.1 (2)	10.5 (2)
Posttraumatic	4.5 (1)	10.5 (2)
Other	22.7 (5)	5.3 (1)
Side (% (N), right)	68.2 (15)	47.4 (9)

ASA classification= American Society of Anaesthesiologists classification

Primary outcome measure

Intra-articular administration of bupivacaine did not affect postoperative pain scores in comparison with placebo, neither as group-effect (p=0.68), nor dependent on time (group*time: p=0.87). In Figure 8.1 the pre- and postoperative pain scores are outlined for both study groups.

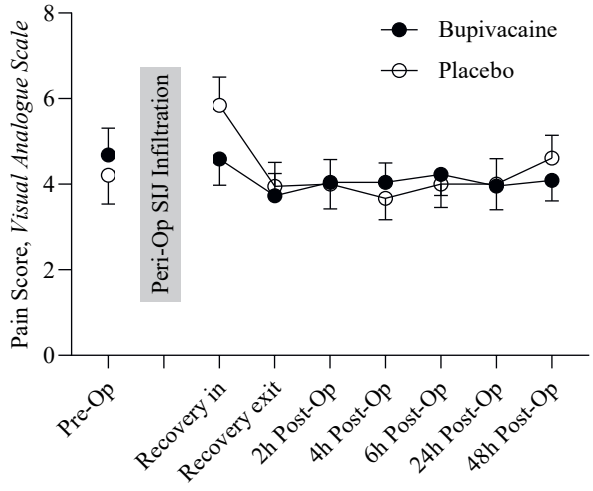

Figure 8.1 Pain scores pre- and postoperative. OP= operative.

Secondary outcome measures

Bupivacaine did not affect opioid consumption at recovery or during the remaining 48 hours postoperative period in comparison with placebo (p=0.81) (Figure 8.2). Patient reported recovery (GSRI), satisfaction and back and leg pain (VAS) at 24 hours postoperatively did not differ between study groups (Table 8.2). There were also no differences in length of hospital stay or complications rates between bupivacaine and placebo group. The sole complication that occurred was one postoperative wound infection in the placebo group, which was resolved with antibiotic treatment.

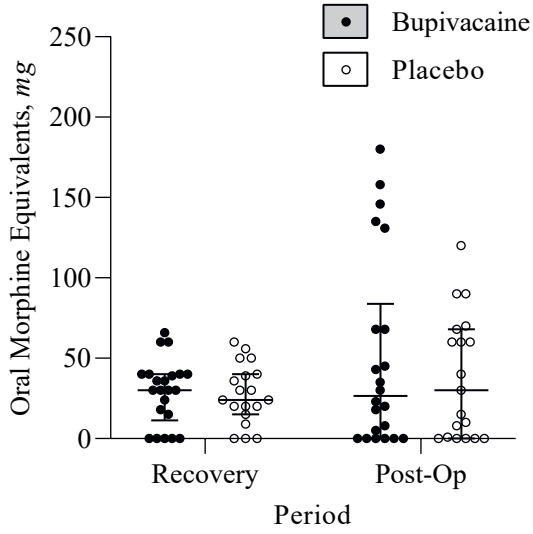

Figure 8.2 Postoperative opioid consumption. Data is presented as individual data, and median and interquartile range.

Table 8.2 Secondary outcome measures.

Variable	Bupivacaine (N=22)	Placebo (N=19)	p-value
Duration of surgery, min	43.18 (9.10)	41.79 (8.32)	0.61
Recovery, GSRI	49 (27)	57 (25)	0.36
Satisfaction, VAS	73 (21)	79 (22)	0.36
Pain – back, VAS	37 (30)	27 (28)	0.30
Pain – legs, VAS	36 (32)	32 (25)	0.70
Length of Stay	1.4 (0.7)	1.5 (0.8)	0.49
Complications <30 days	0	1	0.29

Data is presented as mean and standard deviation, or as frequency (complications). Abbreviation: GSRI= General Surgery Recovery Index, VAS= Visual Analogue Scale. GSRI and VAS were taken 24 hours postoperatively.

Discussion

The most important finding of this study is that intraoperative SIJ infiltration with bupivacaine did not affect postoperative pain during the whole post operative period in comparison with placebo. The lacking effect of bupivacaine on pain is somewhat surprising, as it can affectively generate a diagnostic block. We hypothesize that the lack of pain response is due to postoperative pain following MISJF being mostly caused by iatrogenic injury to surrounding tissues and not the SIJ itself. This is supported by the theorem that the joint is fixed by three implants during surgery, directly limiting motion and perhaps pain. Thus, infiltrating the SIJ might be less effective than infiltrating the wound (soft tissue). Moreover, the latter has been deemed effective in other orthopedic procedures.[11–13] In this perspective, a study comparing analgesia with placebo for wound infiltration after MISJF might be interesting to conduct. Alternatively, part of the ineffectiveness of bupivacaine to influence postoperative pain might be due to the patient group itself. To elaborate, first, it is known that SIJ dysfunction is accompanied with diagnostic delay, hence patients often suffer from complaints for a long period of time before correct treatment is started. During the diagnostic trajectory often large amounts of pain killers are consumed, including opioids. The percentage of patients with SIJ dysfunction that consume opioids is around 40%.[23] Several studies have provided evidence for altered pain perception, known as opioid-induced hyperalgesia in people consuming opioids for an extended period.[24] Second, in recent literature it has become clear that pain catastrophizing is a predictor of pain severity among individuals with persistent musculoskeletal complaints. Pain catastrophizing is considered as a maladaptive coping strategy involving an exaggerated response to anticipated or actual pain.[25] Following spinal surgery around 20% of patients have persistent or recurrent pain in the back or limbs.[26] Moreover, patients that tend to catastrophize are more likely to have higher pain scores in the early postoperative period.[27,28] Patients with SIJ dysfunction that have an extended diagnostic trajectory, consume large amount of pain killers and report a low quality of life seem sensitive for psychological factors like pain catastrophizing.[29] Both altered pain perception and unfavorable psychological factors might have adversely influenced the effect of bupivacaine to reduce pain in the current study group.

In line with the primary outcome, perioperative administration of bupivacaine did also not affect secondary outcomes, such as postoperative opioid consumption. As expected, postoperative pain and opioid consumption are

closely associated. Opioids are a standard component of pain management following spinal surgery, and their utilization should reflect the severity of postoperative pain. As can be seen in Figure 8.2, opioid consumption in the first 48 hours postoperatively is highly variable across patients. Patient-specific factors, such as individual pain thresholds and psychological factors, may influence opioid consumption. One can also expect there is a correlation between pre- and postoperative opioid consumption in patients undergoing MISJF. When a patient has been taking high doses of opioid consumption for a longer period, it is expected that this person will continue the need for opioids following MISJF.[30]

Lastly, while clinical outcomes such as other patient reported outcome measures (VAS recovery, satisfaction and back and leg pain), length of stay and complications showed descent results after MISJF, a surprising observation was the persistent pain after 48 hours, comparable to preoperatively (Figure 8.1). This is contrary to the typical expectation of pain decreasing over time postoperatively. We faced a challenge in verifying this observation since there was no available literature for comparison. Nevertheless, it is worth noting that most patients were discharged within the first day, suggesting pain was manageable, even though the pain scores remained consistently high during this period. Alternatively, patients may have sooner than expected reduced the use of pain medication, which would be a positive observation. Unfortunately, timing of pain medication was not observed detailed enough for substantiating this hypothesis.

Strengths and limitations

The strengths of this study were the prospective, RCT-design in a multicenter setting, involving two high-volume MISJF centers in the Netherlands. This increases the generalizability of the results. A limitation in the presented study is that we did not apply intra-articular contrast. Therefore, it is uncertain whether the intraoperative infiltration was indeed intra-articular and not peri-articular. Though several studies have demonstrated that peri-articular infiltration of analgesia is as effective in reducing pain complaints arising from the SIJ as intra-articular infiltration, and therefore, we do not expect this uncertainty to relate to any bias in study outcomes.[22,31,32] Lastly, the current study exclusively tracked postoperative morphine consumption, potentially leaving variations in the use of other analgesics, such as NSAID's, unaccounted for among patients. This is also the case for anti-emetics. Nevertheless, it is

reasonable to presume that any disparities in this regard are mitigated due to the randomized design of the study.

Conclusion

Intra-articular infiltration of the SIJ with bupivacaine following MISJF surgery is not effective in reducing postoperative pain complaints, nor in reducing opioid consumption compared to placebo. While it is safe, we do not recommend routine use of intraoperative SIJ infiltration with analgesia in MISJF.

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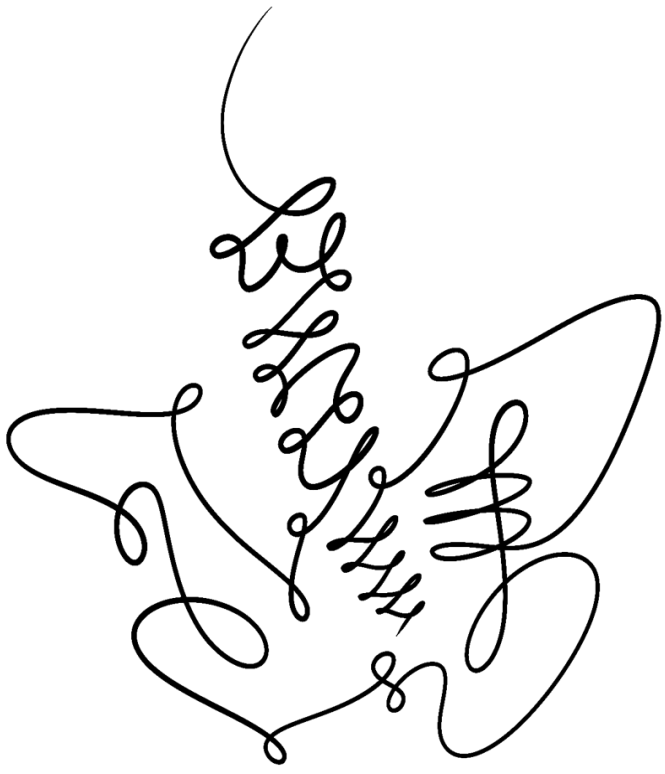
Appendix 8.1

Additional File 8.1 – Opioid conversion table

Opioid	Dose	Morfine per os equivalent	Factor
Piritramide	15mg	30mg	2
Sufenta	0.01mg	30mg	3000
Oxycodon	20mg	30mg	1,5
IV morphine	10mg	30mg	3
Remifentanyl	0.1mg	30mg	300
Afentanil	0.5mg	30mg	60
Fentanyl	0.2mg	30mg	150



Chapter 9

General discussion

General discussion

The sacroiliac joint (SIJ) is increasingly being recognized as a cause of chronic low back and buttock pain.[1] Chronic low back pain is one of the most frequent reasons for individuals to seek healthcare services.[2] In order to provide adequate therapy, it is important to formulate the correct diagnosis. Causes like SIJ dysfunction, attributing to almost 25% of cases of chronic low back pain, should therefore not be overlooked.[3,4] SIJ dysfunction and its therapies remain relatively unfamiliar for a significant portion of healthcare providers. In the current Dutch guideline "treatment options for SIJ dysfunction", it is recommended to focus on conservative treatment options, including oral analgesic use, physical therapy and SIJ belts.[5,6] In patients that have insufficient or no effect from conservative treatment options, intra-articular infiltration with corticosteroids and/or radiofrequency denervation may be considered. Surgical interventions are not advised for individuals with SIJ dysfunction. Nevertheless, the possibility of surgical intervention may be contemplated in cases where patients exhibit confirmed SIJ dysfunction, and their pain persists despite undergoing conservative treatment options. These patients are occasionally referred to one of few centres in the Netherlands in which minimally invasive sacroiliac joint fusion (MISJF) is performed. There is no established standard surgical criterium for SIJ dysfunction. According to recent studies and prevailing clinical practices, eligibility for MISJF typically requires a positive diagnostic SIJ intraarticular injection, evidenced by a 50% reduction in pain.

In **chapter two**, the systematic review and meta-analysis methodology provides a comprehensive examination of the comparative effectiveness of MISJF compared to conservative management for patients with SIJ dysfunction. The systematic review and meta-analysis approach stands as a recognized and robust method in synthesizing existing evidence. By focusing on studies comparing MISJF with conservative treatment, the goal was to enable a precise comparison. However, due to this specific focus, caution should be exercised when extrapolating the findings to a broader population. While demographic similarities between the included studies and the SIJ dysfunction population support some external validity, it is crucial to recognize inherent limitations in generalizability. Another notable limitation are the small sample sizes inherent to the strict inclusion of studies, again influencing the reliability and generalizability of the results. Several systems are described in current literature to establish MISJF.[7,8] The effectiveness of different implant systems seems to

vary across the current literature. Multiple trials investigated the efficacy of cannulated triangular, titanium implants, with clinically significant improvements in pain and disability.[9–14] For other systems, such as titanium cages and hollow modular screws, significantly less evidence in the literature is available.[15] To enhance homogeneity, the focus of the review was exclusively on cannulated triangular titanium implants. This factor naturally contributed to the aforementioned small sample sizes. A critical aspect of the review pertains to the funding sources of the included studies, revealing a predominant reliance on industry support. While common in medical research, this introduces the potential for bias in reporting of results. The findings, suggestive of a place for MISJF in SIJ dysfunction, should be considered in the context of industry funding bias. Considering the mentioned limitations, there is an imperative call for industry-independent studies with adequate methodology to validate and strengthen the conclusions.

Beyond the systematic review and meta-analysis, numerous studies not included in the review detailed clinical outcomes after MISJF. Despite not meeting the inclusion criteria, these studies highlighted significant improvements in clinical outcomes. Specifically, they reported noteworthy advancements in terms of pain reduction and enhanced mobility. 77.1% to 93.8% of patients were satisfied after surgery with a mean follow-up of 20 months. To add clinical evidence to the already existing literature, **chapter three** discloses the one-year findings following MISJF in an independent observational study conducted across two centers. Most patients in this study were female (86.2%), with an average age of 45.6 years. The cause of SIJ dysfunction predominantly was of postpartum origin (44.8%), followed by Ehlers-Danlos Syndrome (EDS) (13.8%). This cohort significantly differs from those in existing literature, particularly in prevalence of postpartum and EDS cases.[16,17] This difference potentially limits the generalizability of the results, which may be attributed to variations in geographical and cultural factors influencing healthcare-seeking behaviors, diagnostic protocols, and cultural attitudes towards postpartum care. The Netherlands, also known for progressive healthcare practices, might exhibit heightened awareness and openness to conditions like EDS, potentially influencing higher diagnosis rates. Surgery for SIJ dysfunction as a result of EDS was described in 2021 by our colleagues in Medical Spectrum Twente, Enschede.[19] Herein, a retrospective case-series of 16 patients was described with a mean satisfaction score of 78.1 out of 100.

Examining the outcomes of the observational study in **chapter three** reveals improvement in pain and overall quality of life, associated with a favorable satisfaction rate and a low incidence of (serious) adverse events one year postoperatively. However, in contrast to findings in the established literature, the results, while positive, suggest a somewhat more modest improvement in pain- and quality of life scores. This variance could potentially be attributed to distinctions in the study population, notably the significant representation of patients with SIJ dysfunction stemming from postpartum causes or EDS. Thus, one can wonder if MISJF is less advisable for these patient groups. Patients with EDS often suffer from chronic pain as a major source of disability, possibly limiting the postoperative pain reduction or quality of life.[20] It can also be postulated that wrong indications or other patient-related factors, such as patient expectations, are of influence on the outcome, which is commonly encountered in other spinal surgical procedures.[21,22] Additionally, exploring patient expectations and subjective pain experiences in terms of mental states, assessed through questionnaires like Hospital Anxiety and Depression Scale (HADS) and Pain Catastrophizing Scale (PCS), could provide valuable insights. It is worth noting that these aspects were not investigated in the current thesis, and their potential impact on outcomes remains a direction for future research.

The initial chapters explore the potential and preliminary outcomes of MISJF in SIJ dysfunction. Shifting the focus in subsequent **chapters four, five, and six** towards research on physical activity and motion analysis in patients with postpartum SIJ dysfunction. These chapters aim to deepen the understanding of pathology and disease burden, introducing objective outcome parameters alongside subjective measures. While recognizing the crucial role of subjective outcomes in assessing MISJF effects, there is a growing interest in objective data. The need for such data is underscored by skepticism surrounding SIJ dysfunction diagnosis and treatment, possibly rooted in factors like unique patient characteristics, pain catastrophizing, diagnostic challenges, and industry funding of clinical studies, which may introduce biases. Objective data, as demonstrated by studies in various musculoskeletal diseases, becomes imperative for a comprehensive evaluation of treatment efficacy, providing insights that complement self-reported outcomes.

Physical activity improvement after hip and knee arthroplasty is surprisingly negligible, despite significant enhancements in self-reported outcomes related to physical activity.[23–26] For postpartum SIJ dysfunction, **chapter four** also

demonstrates that physical activity does not improve three months following MISJF, while quality of life significantly improves. Overall physical activity is comparable to that of matched controls. This incongruity prompts a closer examination of the relationship between physical activity and quality of life in the postoperative period. One potential explanation for the dissociation between the two could be that the impact of MISJF on overall well-being, captured by improvements in quality of life, may not manifest immediately in enhanced physical activity. It is plausible that three months following surgery might be a premature moment to observe significant changes in physical activity, suggesting the need for a more extended follow-up period. As mentioned in the introduction, fusion is anticipated to occur around three months postoperatively. Additionally, individual variations in response to surgery and the influence of factors such as pain perception, psychological adaptation, and postoperative rehabilitation could contribute to this nuanced relationship between quality of life and physical activity.

Moving to **chapter five and six**, the decision to study qualitative motion analysis over quantitative motion stems from the absence of substantial differences between patients compared to matched controls in **chapter four**. The feasibility study in **chapter five** reveals significant differences in terms of motion patterns between patients with postpartum SIJ dysfunction compared to matched controls. A disturbed gait, less balance and slower movement are observed. Confirming low disability in patients with SIJ dysfunction, as literature describes a mean Oswestry Disability Index score of 56.2 in patients before MISJF, interpreted as severe disability.[8,27] In **chapter six**, the same motion analyses are performed on the identical group of patients, three months post-MISJF. While quantitative motion, measured through physical activity (**chapter four**), did not exhibit improvement during this period, there are notable enhancements in qualitative motion. In numerous parameters, the motion patterns demonstrated by the patients are now comparable to those of matched controls, with significant improvements observed in balance and tasks such as performing a sit-to-stance. These findings indicate that the latter tasks are less painful to perform, thus MISJF seems to result in short term qualitative motion pattern improvements. However, the absence of notable changes in gait parameters raises questions about the optimal timing for assessing post-MISJF motion improvements. The three-month postoperative period may be a premature moment, and longer follow-up intervals could provide a more comprehensive understanding of the evolution of gait changes over time. The

complex scenario of persistent contralateral SIJ complaints in a subset of patients, requiring a second surgery for further symptom relief, underscores the multifaceted nature of SIJ dysfunction. This highlights the importance of individualized patient management and suggests the potential for ongoing improvement with subsequent surgical interventions. Additionally, the reliance of the study on a one-day measurement for motion analysis prompts consideration of the potential variability in movement patterns on different days. This is especially important given the influence of potential psychological factors within this challenging study group. Further exploration, perhaps with an extended and repeated assessment duration and attention to psychological aspects, holds promise for unveiling the nuanced dynamics of post-MISJF motion patterns and functional improvements.

The previous chapters of this thesis delve into the clinical outcomes of MISJF, revealing encouraging results. While the observed effects of MISJF hold promise in terms of both subjective and objective clinical outcomes, a cautious approach is warranted. Justifying MISJF as a recognized standard surgical indication necessitates additional robust data from well-powered, industry-independent, and randomized controlled trials (RCT) with validated outcome measurements. This imperative holds particularly true for addressing emerging sources of SIJ dysfunction, such as EDS or postpartum cases. Furthermore, the existing literature on the cost-effectiveness of MISJF is limited. In the forthcoming SACRIFICE study, detailed in the protocol outlined in **chapter seven**, the aim is to conduct an industry-independent RCT comparing MISJF to prolonged, standardized, conservative treatment. This study will provide a comprehensive assessment of both clinical and economic effects. This study must aid in the revision of current guidelines for treating SIJ dysfunction in the Netherlands. If the proposed study shows greater (cost-)effectiveness of MISJF compared to conservative treatment, MISJF may be implemented in guidelines, leading to standard and continues reimbursement from Dutch healthcare providers. If the hypothesis is not confirmed, MISJF procedures can be avoided. Simultaneously, responder/non-responder analyses will be sought to (in)validate current clinical experience.

Pending the findings from the SACRIFICE study, it appears that certain individuals with SIJ dysfunction may experience favorable clinical outcomes with MISJF. In the following chapter of this thesis, emphasis is placed on the perioperative care for individuals undergoing MISJF procedures. The observed

trend reveals that patients commonly report significant pain during the initial postoperative days. Managing postoperative pain proves challenging, particularly within a patient demographic characterized by prevalent chronic opioid consumption, as detailed in **chapter three**. Persistent postoperative pain may prevent early mobilization, which is important following orthopaedic procedures. In addition, postoperative pain contributes to patients taking high doses of analgesics. Analgesics, especially opioids, can cause nausea and drowsiness, resulting in a prolonged hospitalization period.[28] Postoperative pain and nausea are also a major cause of a negative experience of hospitalization.[29] In order to improve perioperative care in MISJF, **chapter eight** evaluates the effectiveness of intraoperative SIJ infiltration with analgesia (bupivacaine 0.50%) in reducing postoperative pain after MISJF in a double-blind RCT. The results demonstrate that local analgesia through an intraarticular injection of bupivacaine at the conclusion of surgery is not effective in reducing postoperative pain complaints, nor opioid consumption compared to placebo. Consequently, it is not advocated to intraoperatively infiltrate the SIJ with analgesia in MISJF. As noted in the thesis introduction, SIJ dysfunction often experiences diagnostic delays, contributing to elevated opioid consumption.[30] Various studies suggest opioid-induced hyperalgesia as a potential explanation for prolonged high pain levels post-surgery.[31] The latter might be a potential explanation for the findings in **chapter eight**. Psychological factors, such as pain catastrophizing, may also play a role. [32] Pain catastrophizing, characterized by an exaggerated response to anticipated or actual pain, has been linked to higher postoperative pain scores in spinal surgery. [33,34] Given the protracted diagnostic journey, substantial painkiller usage, and reported low quality of life among SIJ dysfunction patients, sensitivity to psychological factors like pain catastrophizing could be a contributing factor. [35] This suggests the need for a holistic approach that encompasses the exploration of behavioral factors and coping mechanisms as potential components to optimize the overall management of postoperative pain. Finally, the question is raised whether targeting the joint directly is the most effective strategy for pain reduction, considering the possibility of pain originating from other areas of the body.

Future perspectives and recommendations

To further improve treatment for individuals with SIJ dysfunction, future endeavors should prioritize refining patient selection strategies to eliminate both

overtreatment and undertreatment. As SIJ dysfunction remains a multifaceted condition, exploring alternative treatment options alongside refining the technique for MISJF is paramount. It is imperative to acknowledge that while MISJF shows promise, it is not yet the definitive solution. Future studies should strive for a nuanced understanding of patient characteristics, considering psychological aspects to tailor treatments effectively. Additionally, a continued focus on advancing the MISJF technique and accumulating evidence with extended follow-up periods will contribute to a more comprehensive approach to manage SIJ dysfunction.

Despite increasing evidence of effectiveness for MISJF, controversy remains or physicians are simply unaware of the surgical options in treating SIJ dysfunction. By disseminating gained knowledge on this subject, attention to treatment will increase accessibility for patients outside the adherence areas of the current MISJF clinics. Incorporating novel diagnostic tools, such as biomechanical assessments or machine learning algorithms analyzing gait patterns, may contribute to a more comprehensive and accurate diagnosis of SIJ dysfunction. These advancements might have the ability to objectively measure patient complaints. From this perspective, the research team plans to perform prolonged follow-up evaluations of the studies presented in **chapter five** and **chapter six**. This study will provide long term objective outcome data on gait, balance and other spatiotemporal parameters following MISJF.

Objective outcome data may also play a role in patient selection for MISJF. Presently, eligibility for MISJF for patients with SIJ dysfunction is based on a positive SIJ intraarticular injection. This test is based primarily on subjective unidimensional pain reports and thus remains limited due to subjective bias and interpersonal discrepancies. This raises the need for a validated objective outcome measurement in SIJ dysfunction for diagnostic and maybe even evaluative purposes. Currently, a pilot study is being performed by our research group to determine clinical applicability of balance during a single leg stance before and after intraarticular SIJ injection as an indicator of SIJ dysfunction. Applicability of this test in a clinical setting seems viable, as a measurement takes about two minutes to explain, set up and perform. In future studies, this test may be assessed as a predictor for surgical outcome of MISJF. These objective outcome data may ameliorate on the subjective reduction of pain outcome following intraarticular injection. Potentially, combining these outcomes may result in better patient selection for MISJF.

Further refining of the surgical procedure in MISJF will ensure the effectives and safety of the operation. Placement of implants may play a critical role in MISJF, as it directly influences the degree of stability in cadaveric biomechanical studies.[36,37] However, the effect on clinical outcome has yet to be further investigated. Correct implant placement prevents complications such as nerve injury. Tools like three-dimensional (3D) CT imaging navigation and robotics hold a promising future in this perspective. Some studies already show encouraging results.[38,39] Improved intraoperative navigation should lead to proper alignment and exact placement location of implants, reducing the risk for errors. Advanced imaging can facilitate in the creation of patient's specific implants, optimizing fit and stability. Robotic assistance may further enhance precision and consistency of implant placement during the procedure, as well as minimizing radiation exposure and reducing a surgeon's learning curve. The latter may lead to more surgeons who can perform MISJF safely and effectively. Nonetheless, the cost-effectiveness of 3D CT navigation as well as robotics implementation in MISJF should adequately be assessed to judge whether it can play an important role in its eventual assimilation into everyday practice.

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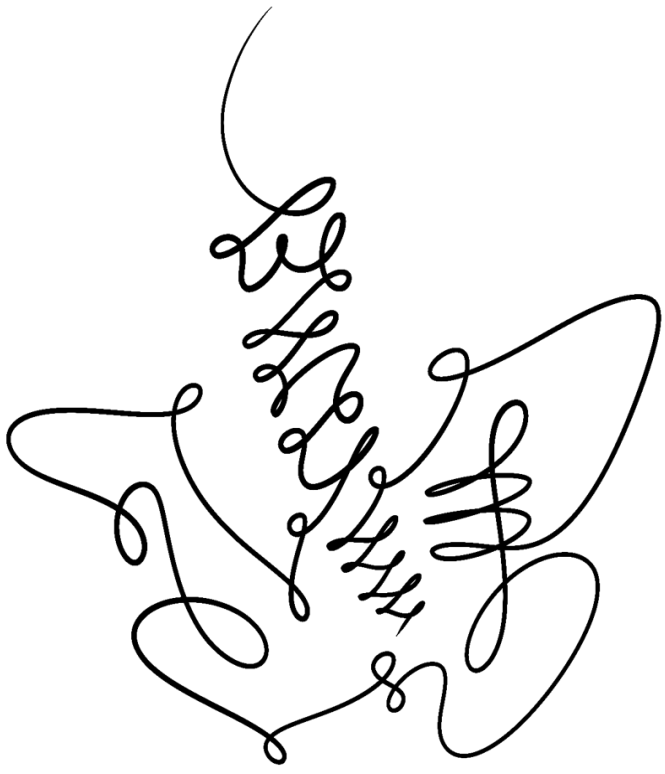

Chapter 10

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This thesis is a comprehensive exploration of sacroiliac joint (SIJ) dysfunction and its potential interventions. It starts by examining the etiology and available treatment options, then delves into the effectiveness of minimally invasive sacroiliac joint fusion (MISJF) compared to conservative management. The research encompasses observational studies, evaluating clinical outcomes and safety post-MISJF, and investigates the impact on physical activity and motion patterns. Notably, the protocol for the SACRIFICE study introduces a multicenter randomized controlled trial (RCT), aiming to assess MISJF versus conservative therapy, with a focus on both clinical and economic effects. The thesis concludes with a prospective RCT on intraoperative SIJ infiltration for postoperative pain management. This multifaceted approach contributes valuable insights into SIJ dysfunction, considering clinical, economic, and broader management perspectives.

In addition to most current literature, it was observed that SIJ dysfunction often occurs in female patients following pregnancy and patients that suffer from Ehlers Danlos Syndrome (EDS) (**chapter three**). It is advised to evaluate the SIJ, especially in these patients who present with chronic low back pain with an unrevealing spine evaluation. A diagnostic SIJ intraarticular injection should be performed to eventually confirm SIJ dysfunction.[1,2] It is suggested that MISJF can be considered when a patient has failed conservative therapies, has persistent complaints and functional impairment. This statement is not solely based on subjective clinical outcomes, but also on short-term objective outcome measures in the form of physical activity and motion patterns with reasonable results (**chapter four, five and six**). Collecting these results is highly valuable in addition to the better-known clinical results, such as patient-reported outcome measures (PROMs). Additionally, it provides insights into the functional impact of SIJ dysfunction, offering valuable data to evaluate the effectiveness of both surgical interventions and conservative therapies. These collective findings contribute to refining the evaluation and potential diagnostic criteria for SIJ dysfunction, representing a leap forward in improving clinical approaches and decision-making within the healthcare domain.

Implementing MISJF in SIJ dysfunction treatment may not only attribute to improving chronic low back pain treatment in terms of clinical effect, but also in terms of economic effect. Chronic low back pain is responsible for significant

direct and indirect costs.[3] Non-specific low back pain affects people of all ages and is a leading contributor to disease burden worldwide.[4] It is hypothesized that a significant proportion of these patients have complaints of the often-overlooked SIJ. Elevating the consideration of the SIJ as a prevalent contributor to chronic low back pain holds the promise of diminishing diagnostic delays and subsequently reducing treatment delays. This shift in focus, encompassing both conservative and surgical approaches, particularly in the form of MISJF, is anticipated to result in decreased healthcare costs. Definitive conclusions on this matter are expected upon the completion of the SACRIFICE study (**chapter seven**).

The findings in this thesis carry significance for a broad audience, including policymakers, healthcare professionals, and, notably, individuals with SIJ dysfunction. For policymakers, the results provide valuable insights into the treatment effects of MISJF in addressing SIJ dysfunction. These insights can be instrumental in informing healthcare professional clinical practices, offering them new perspectives on the clinical outcomes of MISJF and a deeper understanding of SIJ dysfunction in general. This may prompt healthcare providers to consider referring such cases to specialized centers performing MISJF in the Netherlands. This approach aligns with the concentration of healthcare expertise, ensuring patients receive specialized care tailored to their specific needs. Finally, individuals with SIJ dysfunction may gain from our results because of the potential beneficial effects of MISJF. As mentioned before, most affected patients according to our research are middle-aged women who suffer from EDS or developed complaints after pregnancy. Notably, for these individuals, opting for MISJF may not only contribute to the amelioration of their symptoms and functional impairment but could also carry positive economic implications. Considering that many of these women are in their work years, the potential improvement in their health through MISJF may translate into enhanced work productivity and reduced economic burden associated with chronic health issues.

Knowledge dissemination of the results of this thesis was realized through presentations at national and international conferences and in scientific journals. Moreover, this thesis subject has provided opportunities for four students of the bachelor's program Physiotherapy and Biometrics, and master's program Medicine to conduct their thesis research projects. In anticipation of the SACRIFICE study, the collaborative efforts among the three MISJF-performing

centers in the Netherlands have been pivotal in shaping the design of this multicenter RCT. Notably, our collaborative history with Medical Spectrum Twente, one of the participating centers, underscores a productive partnership. Furthermore, the engagement of the national EDS society in crafting the SACRIFICE study protocol and its ongoing involvement throughout the study reflects a commitment to a comprehensive, multidisciplinary approach. This thesis serves as a foundational step toward crafting new national treatment guidelines for SIJ dysfunction. The collaborative, multi-centric efforts have enriched our understanding of the pathology and resulted in the establishment of a multicenter RCT. This positions the study to offer insights that may impact future updates to existing guidelines from 'Federatie Medisch Specialisten'. This marks a significant stride towards optimizing SIJ dysfunction management and embracing a more inclusive and informed approach.

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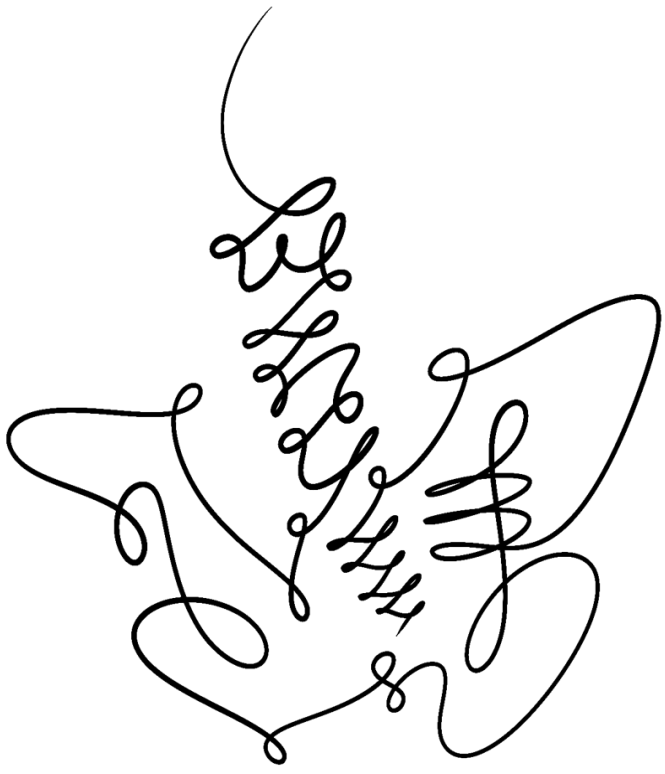


Chapter 11

Summary

Summary

The current thesis encompasses a thorough investigation into sacroiliac joint (SIJ) dysfunction, with attention for effectiveness of diagnosis, surgical treatment and outcome.

Chapter one provides a general introduction of the global prevalence and impact of low back and buttock pain, emphasizing the often-overlooked role of SIJ dysfunction. The chapter covers the anatomy and function of the SIJ, discussing its innervation, motion, and the importance of form and force closure in maintaining stability. Various factors contributing to SIJ dysfunction, including posttraumatic, degenerative, postpartum, post lumbar fusion surgery, and connective tissue disorders, are discussed. Challenges are discussed in diagnosing SIJ dysfunction, outlining symptoms and diagnostic tests, and emphasizes the limited role of imaging. Management strategies, ranging from conservative approaches to surgical options like MISJF, are detailed. The societal impact and costs are briefly touched upon.

Chapter two comprises a systematic review and meta-analysis on the effectiveness of MISJF compared to conservative management in patients with SIJ dysfunction. Exploration of the literature indicated a limited availability of studies which met the strict inclusion criteria. Two randomized controlled trials (RCT's) and one retrospective cohort study were included, encompassing 388 patients (207 conservative and 181 surgical). In a pooled mean difference analysis, MISJF demonstrated greater reduction in Visual Analogue Scale (VAS) pain score compared to conservative management; -37.03 points. Moreover, MISJF was associated with a greater reduction in Oswestry Disability Index outcome; -21.14 points. Additionally, one cost-effectiveness analysis was included and favored MISJF. The outcomes of this review must be interpreted with caution due to the important limitation of the small sample size.

Chapter three presents a double-center observational study to investigate the clinical results and safety of MISJF over a one-year observation period at Zuyderland Medical Center and Medical Spectrum Twente. A total of 29 patients were included. In 44.8% of patients SIJ dysfunction was of postpartum origin. Statistically significant and clinically relevant improvements in pain (VAS-pain score improved from 7.83 (±1.71) to 4.97 (±2.63)) and quality of life (EQ-5D-3L score, improved from 0.266 (±0.129) to 0.499 (±0.260)) were observed

one-year postoperatively. Opioid consumption decreased from 44.8% to 24.1% postoperatively (p=0.026). In 13.7% of patients an adverse event (AE) occurred, comparable to current literature.

Chapter four explores physical activity in patients with postpartum SIJ dysfunction before and after MISJF compared to age-, BMI-, gender- and postpartum-matched controls. Physical activity was measured using triaxial accelerometer for seven consecutive days, before surgery and three months after surgery. The study revealed that physical activity in patients with postpartum SIJ dysfunction does not improve three months following MISJF, while quality of life does improve significantly. The discrepancy between these two observations raises questions about the relationship between quality of life and physical activity.

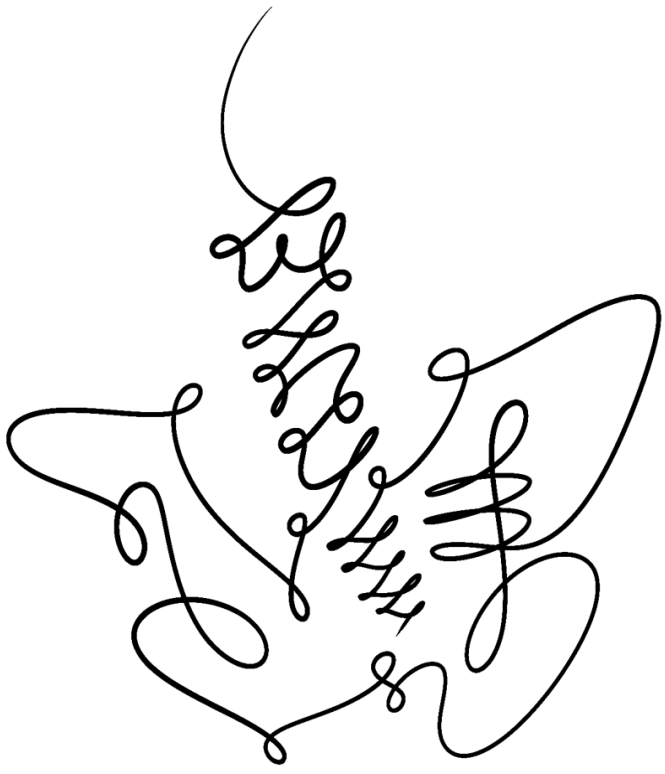
Chapter five is a cross-sectional case-control study that aims to investigate spatiotemporal parameters, center of pressure and mass, pelvic angles and other joint angles in patients with SIJ dysfunction in comparison with healthy controls. Thirty subjects were recruited for this study; ten patients, ten matched controls and ten healthy student controls. Patients showed an impaired gait, with a lower cadence, longer double support phase, shorter step length and slower walking speed than controls. Also, more balance problems during standing on a single leg and standing up from a chair were observed compared to controls.

Chapter six is the longitudinal follow-up study of chapter five and is conducted to analyze the changes in motion patterns in patients with SIJ dysfunction three months after MISJF. Balance improvements during a single-leg-stance and a faster sit-to-stance execution time were observed after surgery and were now comparable to that of matched controls. Gait analysis revealed no improvement in any of the measured parameters when comparing pre- and postoperative.

Chapter seven shows the study protocol for the SACRIFICE study. A multicenter RCT for the effectiveness of MISJF compared to prolonged conservative therapy in SIJ dysfunction. The aim of this study is to perform the first industry-independent RCT of MISJF versus conservative treatment with a comprehensive assessment of clinical and economic effects. All included patients diagnosed with SIJ dysfunction will be randomized to either prolonged standardized conservative treatment or operative treatment. Patients in the

conservative group may undergo MISJF earliest after 6 months. The primary outcome is back function. Secondary outcome measures include cost-effectiveness from a healthcare and societal perspective.

Chapter eight presents a prospective, double blind RCT to investigate the effectiveness of intraoperative SIJ infiltration with bupivacaine 0.50% versus placebo (NaCl 0.9%) in reducing postoperative pain after MISJF. Results of the study revealed that bupivacaine is not effective in reducing postoperative pain. No changes in pain scores in comparison with placebo, neither as group-effect ($p=0.68$), nor dependent on time (group*time: $p=0.87$) were present. The secondary outcome parameters, which were opioid consumption, patient satisfaction, adverse events, and hospital stay, were also not different in the postoperative period between study groups.



Chapter 12

Nederlandse samenvatting

Nederlandse samenvatting

Het huidige proefschrift omvat een grondig onderzoek naar disfunctie van het sacro-iliacale (SI) gewricht, met aandacht voor de effectiviteit van diagnose en van de behandeling.

Hoofdstuk één geeft een algemene inleiding over de prevalentie en impact van lage rug- en bil-pijn wereldwijd, met nadruk op de vaak over het hoofd geziene rol van SI-disfunctie. Het hoofdstuk behandelt de anatomie en functie van het SI-gewricht, bespreekt de innervatie, beweging en het belang van vormafsluiting en krachtverdeling voor het behoud van stabiliteit. Diverse factoren die bijdragen aan SI-disfunctie, waaronder posttraumatische, degeneratieve, postpartum, post-lumbale fusiechirurgie en bindweefselaandoeningen, worden gedetailleerd beschreven. Er wordt ingegaan op de uitdagingen bij het diagnosticeren van SI-disfunctie, waarbij symptomen en diagnostische tests worden besproken, met ook aandacht voor de beperkte rol van beeldvorming. Behandelingen, variërend van conservatieve benaderingen tot chirurgische opties zoals minimaal invasieve sacro-iliacale fusie (MISJF), worden uiteengezet. De maatschappelijke impact en kosten worden kort aangestipt.

Hoofdstuk twee omvat een systematische review en meta-analyse over de effectiviteit van MISJF vergeleken met conservatieve behandeling bij patiënten met SI-disfunctie. Uit literatuuronderzoek bleek dat slechts een beperkt aantal studies aan de strikte inclusiecriteria voldeed. Twee gerandomiseerde gecontroleerde studies (RCT's) en één retrospectieve cohortstudie werden geïncludeerd, met in totaal 388 patiënten (207 conservatief en 181 chirurgisch). De gepoolde gemiddelde verschilanalyse toonde aan dat MISJF een aanzienlijk grotere afname in de pijnscore op de Visueel Analoge Schaal (VAS) vertoonde in vergelijking met conservatieve therapie (-37,03 punten). Bovendien werd MISJF geassocieerd met een significante reductie in de uitkomst van de Oswestry Disability Index (-21,14 punten). Het review omvatte ook een kosten-effectiviteitsanalyse waaruit bleek dat MISJF kosteneffectiever was dan conservatieve therapie. Vanwege belangrijke beperkingen in het onderzoek, zoals de steekproefomvang, moeten de resultaten met enige voorzichtigheid worden geïnterpreteerd.

Hoofdstuk drie presenteert een dubbel-center observationeel onderzoek om de klinische resultaten en veiligheid van MISJF te onderzoeken gedurende een

observatieperiode van één jaar in het Zuyderland Medisch Centrum en het Medisch Spectrum Twente. In totaal werden 29 patiënten geïncludeerd. Bij 44,8% van de patiënten was er sprake van postpartum SI-disfunctie. Statistisch significante en klinisch relevante verbeteringen in pijn (VAS-pijnscore verbeterde van 7,83 (±1,71) naar 4,97 (±2,63)) en kwaliteit van leven (EQ-5D-3L-score, verbeterde van 0,266 (±0,129) naar 0,499 (±0,260)) werden waargenomen één jaar na de operatie. Het gebruik van opioïden daalde significant, van 44,8% vóór de operatie naar 24,1% na de operatie (p=0,026). Bij 13,7% van de patiënten trad een complicatie op. Dit aantal was vergelijkbaar met de huidige literatuur.

Hoofdstuk vier onderzoekt de fysieke activiteit bij patiënten met postpartum SI-disfunctie voor en na MISJF, vergeleken met leeftijds-, BMI-, geslachts- en postpartum-gematchte controles. Lichamelijke activiteit werd gemeten met behulp van een tri-axiale versnellingsmeter gedurende zeven opeenvolgende dagen, zowel vóór als drie maanden na de operatie. Uit het onderzoek bleek dat de fysieke activiteit bij patiënten met postpartum SI-disfunctie niet verbeterde drie maanden na MISJF, terwijl de kwaliteit van leven wel aanzienlijk verbeterde. Het verschil tussen deze twee observaties riep vragen op over de relatie tussen kwaliteit van leven en lichamelijke activiteit.

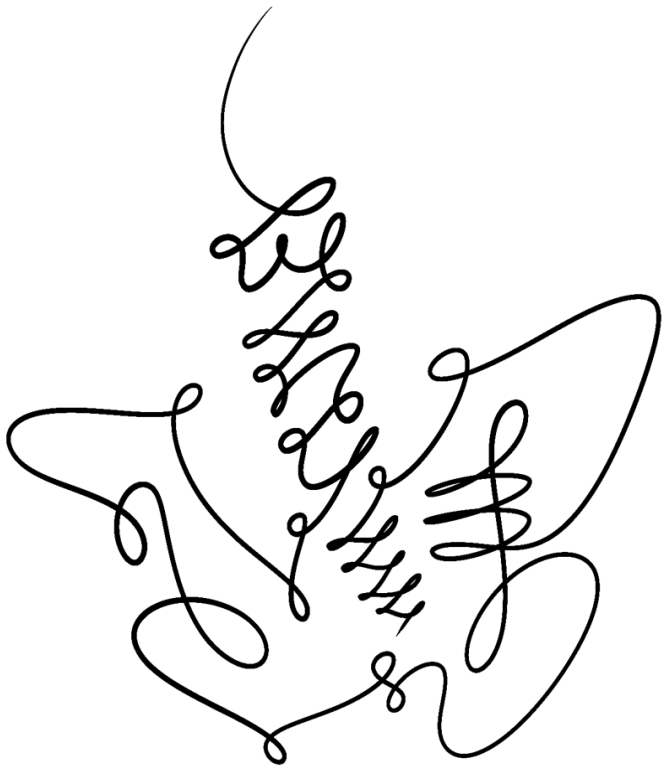
Hoofdstuk vijf is een cross-sectionele case-control studie die het doel heeft spatiotemporele parameters, zwaarte- en drukpunt, bekkenhoeken en andere gewrichtshoeken te onderzoeken bij patiënten met SI-disfunctie in vergelijking met gezonde controles. Voor dit onderzoek werden dertig proefpersonen geïncludeerd, bestaande uit tien patiënten, tien gematchte controles, en tien gezonde controles. De resultaten toonde aan dat patiënten een gecompromitteerde gang vertoonden, met een lagere cadans, een langere dubbele ondersteuningsfase, een kortere staplengte en een lagere loopsnelheid dan de controlegroep. Ook werden er meer evenwichtsproblemen waargenomen tijdens het “staan op één been” en het “opstaan uit stoel” vergeleken met de controlegroep.

Hoofdstuk zes vormt de longitudinale vervolgstudie van hoofdstuk vijf en is uitgevoerd om de veranderingen in bewegingspatronen bij patiënten met SI-disfunctie drie maanden na MISJF te analyseren. Na de operatie werden verbeteringen in evenwicht, tijdens het staan op één been, en een snellere uitvoeringstijd van zit-naar-stand waargenomen, die nu vergelijkbaar waren met die van gematchte controles. De ganganalyse liet echter geen verbetering

zien, ongeacht welke van de gemeten parameters werden vergeleken tussen de pre- en postoperatieve situatie.

Hoofdstuk zeven beschrijft het onderzoeksprotocol van de SACRIFICE-studie, een multicenter RCT die de effectiviteit van MISJF vergelijkt met langdurige conservatieve therapie bij SI-disfunctie. Het doel van deze studie is de eerste onafhankelijke RCT van MISJF versus conservatieve behandeling uit te voeren. Hierbij wordt een grondige beoordeling van zowel klinische als economische effecten verricht. Alle geïncludeerde patiënten met de diagnose SI-disfunctie zullen willekeurig worden toegewezen aan langdurige gestandaardiseerde conservatieve behandeling of een operatieve behandeling. Patiënten in de conservatieve groep kunnen MISJF op zijn vroegst na 6 maanden ondergaan. Het primaire resultaat is de mate van functionele beperkingen door pijn bij lage rugklachten. Secundaire uitkomstmaten omvatten kosteneffectiviteit vanuit zowel een gezondheidszorg- als maatschappelijk perspectief.

Hoofdstuk acht presenteert een prospectieve, dubbelblinde RCT om de effectiviteit van intra-operatieve SI-infiltratie met bupivacaïne 0,50% versus placebo (NaCl 0,9%) te onderzoeken in het verminderen van postoperatieve pijn na MISJF. Uit de resultaten van het onderzoek bleek dat bupivacaïne niet effectief is in het verminderen van postoperatieve pijn. Er waren geen significante veranderingen in de pijnscores in vergelijking met placebo, zowel als groepseffect (p=0,68) als afhankelijk van de tijd (groep*tijd: p=0,87). De secundaire uitkomstmaten, waaronder morfine gebruik, patiënttevredenheid, bijwerkingen en duur van ziekenhuisverblijf, werden in de postoperatieve periode evenmin beïnvloed door bupivacaïne in vergelijking met placebo.



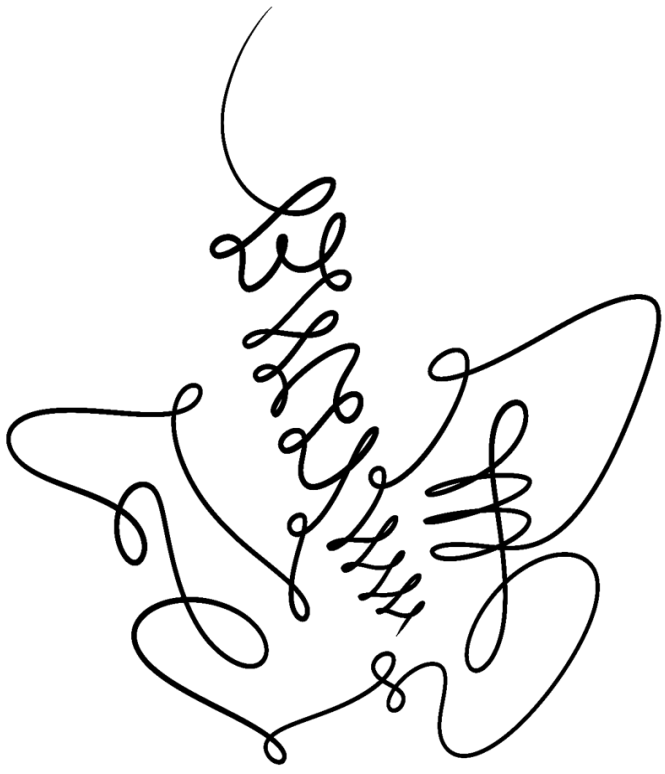
Curriculum Vitae

Curriculum vitae

Sem Markus Maria Hermans was born in Baarlo, the Netherlands, on May 27, 1996. He started competitive swimming at a young age, achieving multiple national championships as a result of his dedication to the sport. After graduating from high school as a LOOT student (National Organization for Education and Elite Sports) in 2015 (VWO, College den Hulster, Venlo), he studied Medicine at Maastricht University. He completed elective internships at the department of Neurosurgery at Maastricht University Medical Center, Maastricht, and at the department of Orthopaedic Surgery and Traumatology at Zuyderland Medical Center, Heerlen and Sittard. It was during these clinical rotations that his interest in spinal surgery further grew.

In his last years of medical studies, he began working on his research under the supervision of Prof. Dr. Henk van Santbrink, Dr. Wouter van Hemert, and Dr. Inez Curfs. Upon graduation from medical school with recognition of a dual career as a Student/Athlete in 2021, he started working as a resident not in training (ANIOS) at the department of Orthopaedic Surgery and Traumatology of Zuyderland Medical Center, Heerlen and Sittard, under the supervision of Dr. Edwin Jansen and Dr. Emil van Haaren. During this period, he combined a clinical and scientific rotation as a PhD Student, leading to this thesis. This combined clinical and scientific rotation was innovative, being one of the first in our region to do so. In 2023, he began his Orthopaedic Surgery training at VieCuri Medical Center, Venlo, within the General Surgery department, under the supervision of Dr. Heinrich Janzing and Dr. Frits Aarts.

While he no longer competes as a swimmer, he still enjoys swimming occasionally. Together with his partner Céline he currently lives in Herten, the Netherlands.



List of publications

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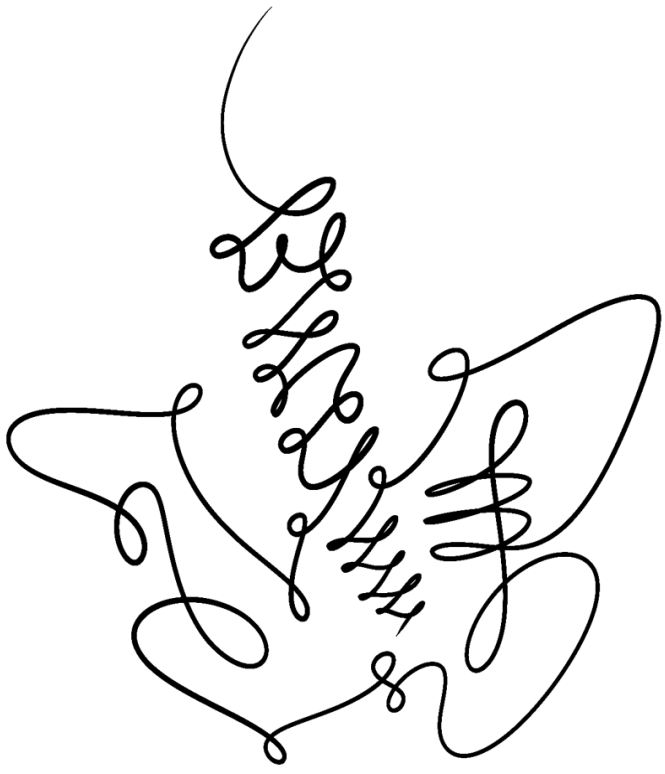

Dankwoord

Dankwoord

Het combineren van een promotieonderzoek met de opleiding tot orthopeed, toewijding aan sport en het koesteren van waardevolle momenten met vrienden en familie is zo nu en dan een evenwichtsoefening. Desondanks werd het evenwicht altijd gehandhaafd dankzij de onvoorwaardelijke steun en begrip van de mensen om me heen.

Allereerst wil ik mijn oprechte dank uitspreken aan alle patiënten die hebben deelgenomen aan de verschillende studies in dit proefschrift. Zonder jullie toewijding en bereidheid om deel te nemen, zouden we nooit deze waardevolle inzichten over sacro-iliacale gewrichtsdysfunctie hebben kunnen verkrijgen.

Prof. dr. Van Santbrink, beste Henk, met oprechte dankbaarheid wil ik jou bedanken voor jouw onschatbare rol als mijn promotor en de kansen die je me hebt geboden. Ondanks het orthopedisch karakter van dit proefschrift, heb jij, als neurochirurg, een buitengewone betrokkenheid getoond. Jouw kritische blik, eerlijkheid en waardevolle feedback hebben een cruciale rol gespeeld in de ontwikkeling van dit werk. Niet alleen binnen het onderzoek, maar ook buiten het werk heb ik altijd kunnen rekenen op jouw advies. De gezellige momenten die we hebben gedeeld, of het nu op congressen was, tijdens een wijnproeverij, of zelfs op die onverwachte skivakantie, maken jouw begeleiding des te waardevoller. Een betere promotor had ik me niet kunnen voorstellen.

Dr. Van Hemert, beste Wouter, jij bent niet alleen een copromotor voor mij geweest, maar ook een mentor. Mijn passie voor de orthopedie is verder aangewakkerd dankzij jouw enthousiasme. Jouw inzicht in het reilen en zeilen van de medische wereld en het verrichten van wetenschappelijk onderzoek heeft me geholpen mijn eigen vaardigheden te verbeteren. Ik wil je hartelijk bedanken voor de kansen die je me hebt geboden, zowel als onderzoeker als arts-assistent. Ik kijk ernaar uit om het orthopedisch vak van je te leren en om nog meer onderzoek samen te bedrijven. We hebben immers nog ideeën genoeg.

Dr. Curfs, beste Inez, als copromotor ben jij een enorme drijvende kracht geweest achter een groot deel van dit proefschrift. Dankzij jouw input en creativiteit hebben we binnen de gestelde tijd onze onderzoeken succesvol kunnen afronden. Jouw vastberadenheid en voorbeeldige werkethos hebben me niet alleen gemotiveerd om mijn doelen na te streven, maar hebben ook een

blijvende indruk op mij achtergelaten. Ik hoop nog veel van jou te mogen leren in de komende jaren, en dat ik ooit de kans krijg om een collega te zijn die jouw voorbeeld volgt.

Leden van de beoordelingscommissie: prof. dr. de Bie, prof. dr. ir. Tuijthof, prof. dr. Verbunt, prof. dr. Verhofstad en dr. Boselie, allen dank voor jullie inzet en tijd om dit proefschrift grondig te bestuderen en te beoordelen. Verder ook dank aan dr. Boonen als overig lid van de oppositie

Beste Ruud, 1/3e van PhDrie, een van mijn beste vrienden. Ik kan eerlijk zeggen dat de tijd als onderzoeker niet hetzelfde was geweest zonder jou. Jouw bijdrage aan dit proefschrift is dan ook van onschatbare waarde geweest. Het is een voorrecht dat we dit samen hebben mogen doen en dat we samen de wereld van de orthopedie verder mogen ontdekken. Als coassistenten in dezelfde terugkomgroep tijdens de master geneeskunde, naar het delen van een plek als ANIOS en onderzoeker in het Zuyderland tot gelijktijdig in opleiding komen, we hebben samen veel mijlpalen bereikt. Geen verassing dat je dan ook als paranimf fungeert vandaag. Ruud, bedankt voor alles. Ik hoop dat we samen nog veel avonturen mogen meemaken.

Beste Valerie, de andere 1/3e van PhDrie. Samen met Ruud hebben we enorm veel onderzoek gedaan, meestal onder het genot van een (of meer) drankjes. Ik kan dan ook zeggen dat zonder jouw hulp dit proefschrift niet zo vlot afgerond zou zijn. Maar je bent veel voor me dan een waardevolle collega, je bent een van mijn beste vrienden geworden. Onze gedeelde ervaringen betekenen veel voor me en ik kijk uit naar nog meer belevenissen. Je bent een van de slimste mensen die ik ken, en ik ben er zeker van dat je een uitstekende neurochirurg zult worden.

Dr. Most, beste Jasper, ik kon altijd op je hulp rekenen wanneer ik opnieuw een vraag had met betrekking tot een van onze onderzoeken. Als rasechte wetenschapper heb jij, met een niet-medische achtergrond, een waardevol perspectief geboden op de verschillende manuscripten. Zonder jouw input op het gebied van statistische en methodologische vraagstukken was dit proefschrift niet tot stand gekomen. Dank voor al je inspanningen.

Dr. Schotanus, beste Martijn, zeker in het begin van het schrijven van dit proefschrift heb jij mij gestimuleerd en geholpen, waardoor ik zelfstandiger kon

opereren bij onze onderzoeken. Bedankt voor jouw begeleiding, maar ook voor de gezelligheid binnen de orthopedie in het Zuyderland.

Evy, jouw input als bewegingswetenschapper was van onschatbare waarde voor een deel van dit proefschrift. De orthopedie zal een waardig orthopeed moeten missen aangezien jij toch voor het huisartsen vak koos. Evy, dank voor je waardevolle hulp bij het vormgeven van een deel van dit proefschrift. Maar bovenal wil ik je bedanken voor het feit dat je een fantastische schoonzus bent. Ik ben blij dat Max bij jou een warm thuis heeft gevonden. Ondanks dat het vanwege de drukke agenda's vaak een uitdaging is, komen Céline en ik altijd graag op bezoek bij jullie mooie huis in Stein.

Beste Remi en Bas, als afstudeeropdracht vanuit de Hogeschool Zuyd hebben jullie gekozen voor het project over bewegingsanalyses bij sacro-iliacale gewrichtsdysfunctie. Ik ben ontzettend dankbaar dat jullie deze keuze hebben gemaakt. Zonder jullie kennis van onder andere Matlab had ik me geen raad geweten. Hartelijk dank voor jullie ondersteuning bij dit proefschrift.

De collega's van Medisch Spectrum Twente, Drs. Nellensteijn, Drs. Knoef en Dr. Schröder, beste Jorm, Rob en Femke, dank voor de constructieve samenwerking gedurende onze gezamenlijke trials. Ik hoop dat we in de toekomst op deze manier kunnen blijven samenwerken.

Beste wervelkolom onderzoeksgroep, in het bijzonder nog te benoemen Dr. Smeets, Anouk, Dr. Caelers, Inge, Dr. Rijkers, Kim, Dr. Boselie, Toon, Drs. van Santbrink, Esther en natuurlijk mijn opvolgster Drs. van Tilburg, Isabelle. Onderzoek doen is geen individuele prestatie, maar eerder een collectieve inspanning. Door samen te werken met jullie wordt onderzoek verrichten nog leuker. We vormen een fantastisch team waarin iedereen altijd voor elkaar klaarstaat wanneer dat nodig is. Bovendien is het altijd gezellig met jullie op congressen of gewoon op de werkvloer.

Beste Sam en Jules, bij de cardiothoracale chirurgie in Maastricht namen jullie mij mee om de eerste stappen als onderzoeker te zetten. Ik wil jullie bedanken voor deze ervaring. Ik ben er zeker van dat jullie beiden een indrukwekkende toekomst tegemoet gaan.

Orthopeden van het Zuyderland, dank voor het warme ontvangst en de ervaringen die ik heb opgedaan als art-assistent onder jullie begeleiding. Jullie vriendelijkheid en toewijding aan onderwijs hebben mijn eerste stappen in de orthopedie buitengewoon waardevol gemaakt. Het was een voorrecht om te leren en te groeien binnen jullie team en ik kijk er naar uit om in de toekomst bij jullie terug te keren als AIOS.

(Oud-)assistenten orthopedie in Zuyderland, hartelijk dank voor de prettige samenwerking en collegialiteit tijdens mijn tijd als ANIOS bij de orthopedie. Jullie steun heeft mijn ervaring enorm verrijkt. Ik kijk ernaar uit om velen van jullie in de toekomst weer op de werkvloer tegen te komen.

Drs. Jeuken, beste Ralph, ik wil jou toch even apart bedanken voor jouw bijdrage aan mijn groei als assistent orthopedie. Ik heb veel van je opgestoken, en we hebben ook veel gelachen. De tips die je me gaf om in de opleiding te komen hebben hun vruchten afgeworpen, je hoeft je schoen niet op te eten! Die sportsessies in je home gym zijn ook gouden herinneringen.

Assistenten chirurgie in Venlo, lieve collega's, wat een feest om met jullie de tent draaiende te houden in het VieCuri. Ik had me geen betere collega's tijdens mijn vooropleiding kunnen wensen. Iedere dag ga ik met plezier naar het werk en dat komt voor een groot deel door jullie.

Beste stafleden van de chirurgie in Venlo, ook jullie wil ik bedanken voor de prettige werksfeer tijdens mijn vooropleiding. Het is altijd een genoegen geweest om met jullie samen te werken. Mijn tijd bij jullie zit er bijna op en ik kan met oprechtheid zeggen dat ik de chirurgie zal missen.

Beste orthopeden in Venlo, inmiddels al in aanraking gekomen met jullie allemaal, en met name met de traumagroep. Bedankt voor de prettige samenwerking. Ik kijk ernaar uit om jullie team binnenkort te komen versterken.

Naast alle collega's van de werkvloer wil ik vooral ook mijn vrienden en familie bedanken. Zonder jullie steun buiten het ziekenhuis was dit proefschrift niet tot stand gekomen.

Tijdens mijn periode in Eijsden heb ik een hoop mensen leren kennen. Ondanks dat we elkaar niet meer zo vaak zien als toen, beschouw ik jullie nog steeds als goede vrienden. Een paar van jullie wil ik persoonlijk bedanken.

De tweeling Laurent en Philip, zwemvrienden vanaf dag één. Wat hebben we veel meegemaakt samen, zowel binnen als buiten het zwembad. Ik kan nog steeds enorm met jullie lachen als we elkaar opzoeken. Hopelijk kunnen we nog vele potjes troven in de toekomst en blijven we elkaar regelmatig weerzien. En natuurlijk mag Toine niet ontbreken tijdens het troven. Toine, ik wil je ook bedanken voor onze onvergetelijke zwemtrainingen in Eijsden. Bedankt voor de intense rivaliteit en de motivatie die je me gaf.

Guy en Raymond, bij LaMeuse flink wat uren samengewerkt, maar vooral ook veel gelachen. Met jullie zijn alle feestjes altijd een waar avontuur. Dank voor jullie vriendschap.

Mijn oude zwemcoaches in Eijsden, Jean en Winand, dank voor jullie eindeloze inzet en de zware zwemtrainingen. Ondanks dat het niet altijd een pretje was om deze pijnlijke trainingen te doorstaan, hebben jullie me gepusht het beste uit mezelf te halen en daar pluk ik nu nog de vruchten van.

Mannen van Licentiatus Medicinae, Beste Ruud, Bob, Stijn, Jarno en Luuk, ik wil jullie bedanken voor onze vriendschap en de mooie studiejaren in Maastricht. Geregeld spreken we elkaar nog en jaarlijks gaan we er een weekendje op uit in België, waarbij plezier gegarandeerd is. Iedereen volgt zijn eigen weg binnen dit mooie vak; ik ben ervan overtuigd dat jullie allemaal succesvol zullen zijn in waar jullie naartoe gaan.

Beste Simon, als mijn studie- en huisgenoot in Maastricht, wil ik je hartelijk bedanken voor de fantastische tijd die we samen hebben doorgebracht. Het gezamenlijk wonen met Max op de Heerderweg zal altijd een dierbare herinnering voor me blijven. Samen sporten, studeren en op stap gaan, jij was altijd aanwezig in die jaren. Hoewel we elkaar nu wat minder vaak zien, kijk ik er enorm naar uit om weer dichter bij elkaar te wonen, wetende dat je binnenkort weer terugkeert naar Limburg. Ik wens je veel succes in je verdere carrière, en ik ben trots dat ik een toekomstige astronaut onder mijn vrienden mag rekenen.

Beste Daniel en Michaëla, bedankt voor de altijd heerlijke weekenden in Willebroek, België. Ondanks dat het een stukje rijden is, maakt jullie warme ontvangst en gezelligheid dat ik graag op bezoek kom.

Beste Max, ik wil je graag bedanken voor alles wat we samen hebben meegemaakt. Je bent niet alleen mijn broertje, maar ook een van mijn meest dierbare vrienden. Ik voel me gezegend dat we zoveel belangrijke momenten samen hebben kunnen delen, zoals onze jeugd in Baarlo, de jaren als wedstrijdzwemmers, samen in de klas zitten op het vwo en studeren aan de universiteit in Maastricht, waarbij we ook nog eens een tijdje huisgenoten waren. Je bent bijzonder vriendelijk, optimistisch en een echte doorzetter, met het voltooien van een Iron Man als bewijs. Ik kijk met opwinding uit naar wat de toekomst voor ons in petto heeft. Bedankt voor jouw voortdurende steun en motivatie.

Lieve mam en pap.
Mam, ik wil mijn waardering en dankbaarheid uitspreken voor alles wat je doet en wie je bent. Je offert je zonder aarzeling op voor anderen, en van jongs af aan heb ik altijd op je kunnen rekenen. Je hebt me aangemoedigd om te dromen en te streven naar mijn doelen, zelfs als de weg moeilijk leek.
Pap, sinds mijn jeugd heb je me geleerd dat hard werken zijn vruchten afwerpt. Ik bewonder je werkethos en hoop dezelfde vastberadenheid te tonen in mijn eigen vakgebied, net zoals jij dat doet in alles wat je aanpakt. Daarnaast hoop ik net zo'n vaardige chirurg te worden als jij handig bent als klusser.
Ik wil jullie beide bedanken voor het warme nest en de onvoorwaardelijke steun. Ik kijk ernaar uit om nog vele mooie herinneringen samen te creëren. Ik ben trots dat jullie mijn ouders zijn.

Lieve Céline, sinds dat we samen zijn was ik al bezig met het vormgeven van dit proefschrift. Als geen ander weet jij wat hiervoor nodig is, aangezien je zelf ook promoveert. Jij bent degene die me helpt alles in perspectief te plaatsen, bij jou voel ik me compleet en begrepen. Dank je wel dat je het met mij volhoudt. Ik weet dat ik altijd op je kan rekenen, wat er ook gebeurt. Jouw liefde en begrip maken elke dag bijzonder. Samen dromen van mooie reizen en het bouwen aan een toekomst met een groot gezin vervult me met opwinding. Ik waardeer je meer dan woorden kunnen zeggen.