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Emerging Magnetic Resonance Imaging Technologies for Musculoskeletal Imaging Under Loading Stress: Scope of the Literature

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Imaging under loading stress is hypothesized to improve the diagnostic value of magnetic resonancel imaging (MRI) for musculoskeletal conditions. This article reviews 57 studies about MRI under physiologic loading stress performed in an upright or sitting position or under axial loading by using a compression device. The most commonly imaged regions were the spine (33 studies) and knee (13 studies). Most studies had a cross-sectional (n = 37) or case–control (n = 13) design and reported on anatomical measurements rather than patient-relevant end points. Studies were generally small: The median (25th, 75th percentile) number of case patients was 26 (17, 45), and the median (25th, 75th percentile) number of control participants was 13 (12, 20 for case–control studies). Fifteen of 57 studies used at least 2 imaging tests and reported on diagnostic or patient-relevant outcomes but did not report meaningful information on the relative performance of the tests. In 10 studies that included information on adverse effects, 5% to 15% of participants reported new-onset or worsening pain and neuropathy during MRI under loading stress. Overall, evidence is insufficient to support the clinical utility of MRI under loading stress for musculoskeletal conditions.

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Musculoskeletal conditions are the most common cause of disability and major source of increased utilization of health care resources in the United States (1–3). According to the American Productivity Audit, 7.2% of the workforce reported having musculoskeletal pain within the previous 2 weeks, and back pain was the second most common cause of missed workdays after headache (4, 5). Similar patterns occur in other industrialized countries (6).

Magnetic resonance imaging (MRI) has emerged as the imaging modality of choice for musculoskeletal disorders, and development of MRI technologies is an active area of research. Often, new technologies are adopted early in their development in the hope of improving patient outcomes, and they sometimes have not yet been rigorously evaluated (7, 8). Multiple studies have identified rapid increases in the use of advanced imaging technologies, particularly those for musculoskeletal conditions (8–10).

The standard clinical MRI scanner configuration includes a large cylindrical magnet. During imaging, the patient lies flat in either a prone or supine position in the bore of the magnet and must remain motionless throughout the imaging period, which ranges from a few seconds to several minutes. This process can induce claustrophobia or anxiety (11).

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Open MRI systems have been designed to overcome certain shortcomings of conventional MRI scanners. In such systems, the bore is open, is typically oriented laterally, and may be shorter than conventional scanners so that only the body part of interest is placed under the magnet. Some open MRI systems are oriented vertically, with the magnets placed to allow an image to be obtained in weight-bearing positions (that is, under loading stress) in which the patient is situated upright (known as "upright MRI") or sitting (**Figure 1**, *top*). Such configurations also allow for flexion and extension views to be obtained (known as "multipositional MRI").

These devices can be used with minimal additional training by MRI facility personnel, and they do not require any specialized installation compared with standard scanners. On the basis of information obtained from device manufacturers, a technology assessment (12) of upright or multipositional MRI reported an estimated cost of $1450 for a single image, with additional views ranging from $350 to $1200.

Imaging under loading stress can alternatively be obtained by placing an axial force on the patient while he or she lies supine in a conventional MRI scanner (**Figure 1**, *bottom*). This approach attempts to simulate gravity by using the compressive force of cords connected to a vest that pull the patient's upper body against a fixed footplate while knees remain in the extended position. Magnetic resonance imaging that involves commercially available axial compression devices seems to have no additional requirements compared with the use of the same MRI devices in unloaded conditions. Compression devices can be used in all conventional (open or closed) MRI scanners on the market.

It has been suggested that MRI under loading stress may be useful for identifying conditions that are challenging to diagnose by using nonloaded MRI, such as cases in which symptoms manifest only in certain positions or only when the joint or body part of interest is stress-loaded or bearing weight (12). We reviewed the literature on imaging under loading stress for musculoskeletal conditions to describe the current state of use of such MRI technologies. We also enumerate the potential benefits and harms of these technologies for the diagnosis and management of patients with musculoskeletal disorders and describe the evidence available to date that supports their clinical application.

Key Summary Points

Imaging under loading stress has been hypothesized to improve the diagnostic value of magnetic resonance imaging (MRI) for musculoskeletal conditions.

Methods for imaging under loading stress include upright, positional MRI in an open scanner and MRI under axial compression to simulate gravity in the supine position. Upright MRI scanners typically have lower magnetic field strength (<1 T) than conventional MRI scanners.

Published studies of stress-loading MRI for musculoskeletal conditions had small sample sizes and often did not report adequate information on diagnostic accuracy or patient-relevant outcomes.

Existing studies have not adequately explored the potential impact of low magnetic field strength on the image quality of weight-bearing (upright) MRI devices.

Comparative studies of stress-loading MRI that reported on diagnostic or patient-relevant outcomes were few and provided insufficient evidence to show the superiority or equivalence of stress-loading MRI compared with alternative imaging modalities.

Many investigations on stress-loading MRI originated from a small number of research teams, thus limiting the generalizability of the findings. Patient population overlap is also a potential concern and suggests that the effective information size is likely to be smaller than the number of available publications indicated.

Despite several theoretical advantages over conventional MRI, imaging under loading stress seems to be at an early development stage, with most studies focusing on non–clinically relevant end points. Considerable uncertainty remains about the utility of MRI under loading stress for the management of musculoskeletal conditions.

METHODS

Protocol

This article was based on a technical brief produced by the Tufts Medical Center Evidence-based Practice Center (Boston, Massachusetts) for the Agency for Healthcare Research and Quality (AHRQ) (13) according to a prospectively developed protocol (14).

Literature Search and Study Selection

We searched MEDLINE from January 1975 to September 2010 for studies that used MRI with weight-bearing or stress-loading protocols in patients with musculoskeletal conditions. We combined Medical Subject Heading or free-text terms for MRI with terms relevant to weight-bearing or loading devices and techniques (for example, dynamic, vertical, and upright) and terms relevant to patient populations (for example, spinal osteophytosis, intervertebral disk displacement, and spinal stenosis). The full text of the technical brief (13) contains the details of our search strategies.

We jointly screened the first 300 citations to ensure that screening criteria were applied uniformly. Thereafter, the same investigators screened nonoverlapping sets of the remaining citations. All citations that a reviewer considered noneligible were screened independently by a second reviewer to increase the sensitivity of the screening process. Thus, we retrieved full-text articles for all citations that at least 1 reviewer considered potentially relevant. We also reviewed the reference lists of all studies considered eligible, as well as those of relevant review articles, to identify additional potentially eligible studies.

We performed additional Internet searches by using Google to identify relevant MRI devices and their manufacturers. Search terms included, but were not limited to, "positional MRI," "upright MRI," "weight-bearing MRI," and "axial loading MRI." For each search string, we reviewed the first 40 results and visited all Web sites that were considered relevant.

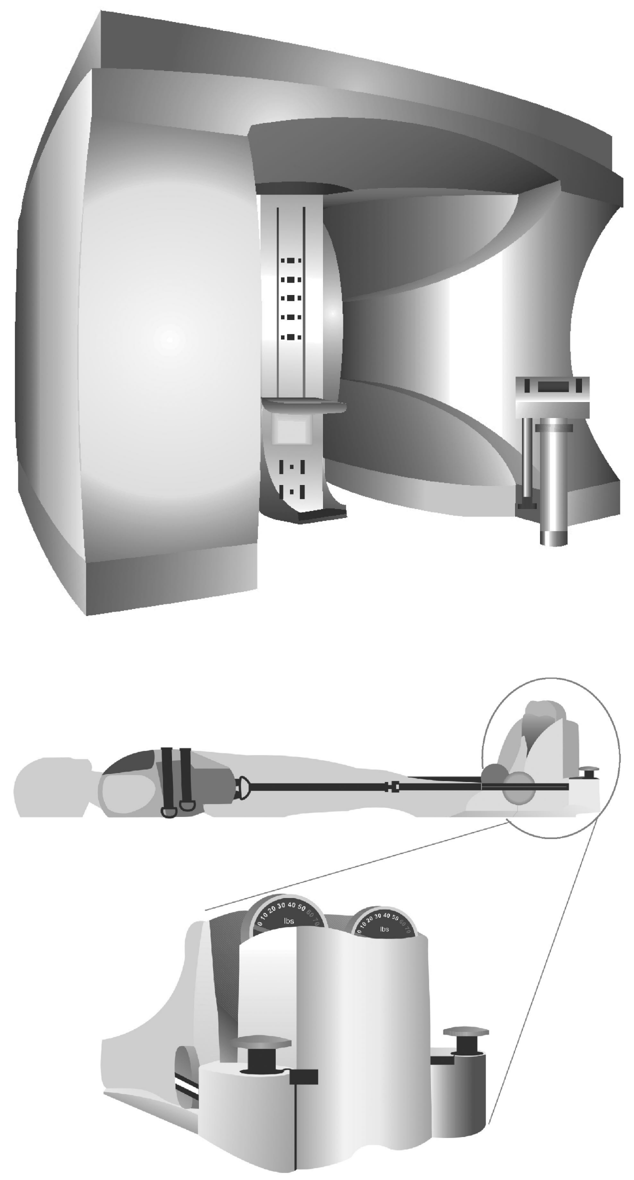
We also searched manufacturers' Web sites for additional information. These searches yielded background information (for example, company brochures) and lists of citations relevant to the devices of interest. In addition, we searched the U.S. Food and Drug Administration (FDA) Center for Devices and Radiological Health database to identify major MRI device manufacturers and to obtain FDA clearance status of relevant MRI devices.

To identify potential harms of relevant MRI devices, we queried the FDA Manufacturer and User Facility Device Experience database by using specific device brand names, manufacturers, or the product code "LNH" (15). We also searched for private insurance reimbursement policies for MRI under stress loading and ClinicalTrials.gov for relevant ongoing studies by using the same terms as our primary Internet searches. Key informants provided additional relevant information.

Study Selection

We included primary studies of any design that provided data on the application of MRI under loading stress

Figure 1. **Computer illustrations of MRI scanners.**



Illustrations reproduced with permission from I-Pei Chung. MRI = magnetic resonance imaging. **Top.** Simplified schematic of an open, upright, weight-bearing MRI device, modeled on the FONAR Upright multipositional MRI (FONAR, Melville, New York). The device allows positional (flexion and extension), weight-bearing (upright and sitting) imaging and has an open configuration. A tilting table placed at right angles between the magnet coils can be positioned at any angle between −20 and 90 degrees vertically, which allows supine and standing imaging. An MRI-compatible seat can be added for imaging in a sitting position, as shown. **Bottom.** Simplified schematic of an axial-loading device used to simulate gravity in the supine position, modeled on the DynaWell L-Spine device (DynaWell Diagnostics, Las Vegas, Nevada). The device consists of a harness attached to a nonmagnetic compression part by straps, which are tightened to axially load the lumbar spine. Tightening or loosening the adjustment knobs on the footplates can regulate and equally distribute the load on the legs.

in at least 10 patients (or a total of 10 case patients and control participants for case–control studies) with any musculoskeletal condition except those affecting the temporomandibular joint. We considered studies of kinematic (dynamic) MRI only if imaging was obtained under stress-loading conditions.

We excluded studies that exclusively recruited healthy persons. We did not consider narrative reviews, editorials, letters to the editor, or other publications not reporting primary research findings. Finally, we did not consider studies published only in abstract form, which often report preliminary findings and are not peer-reviewed.

Data Extraction

We independently extracted the following information from studies that we considered eligible: bibliographic information, study design, condition studied, study size and clinical setting, patient selection criteria, outcomes assessed, and funding sources (16). We also recorded data on the specific loading technique and the technical specifications of the MRI devices. For comparative studies of 2 or more diagnostic tests (1 of which must have involved MRI under loading stress) that reported diagnostic or patient-relevant outcomes, we extracted additional information on the comparators, outcomes, and key findings. We performed a series of calibration exercises to ensure consistency and accuracy of data extraction across investigators.

Building an Evidence Map

We built an evidence map to synthesize evidence from the diverse information sources that we considered (17). A systematic and replicable but potentially nonexhaustive methodology was used to allow efficient appraisal of the available evidence on a topic of interest, as well as identification of major knowledge gaps (17). This approach aimed to provide investigators with information about the type and amount of research available, the characteristics of that research, and the topics on which sufficient evidence has accumulated for synthesis.

We used Stata, version 11.1/SE (StataCorp, College Station, Texas), to generate tables and graphs to summarize information across studies and to calculate summary descriptive statistics about the eligible studies, as appropriate (18). We graphically presented quantitative data by using weighted scatterplots to summarize the sample sizes, study designs, and specific MRI devices investigated in the studies that we reviewed. Further quantitative analyses (for example, meta-analyses) were not conducted because of the diversity of the patient populations and outcomes investigated.

To explore whether particular findings or research groups were overrepresented in the literature, we identified studies that had any overlap in author lists by cross-checking author names and institutions across the studies we reviewed (**Appendix Figure 1**, available at www.annals.org). We defined studies that had any coauthors in common as "conducted by the same research teams." Undirected graphs depicting groups of studies conducted by the same research teams also were generated.

Role of the Funding Source

The study is based on a technical brief prepared under contract with the Agency for Healthcare Research and Quality. The funding agency had no role in the design, conduct, or analysis of this study or in the decision to submit the manuscript for publication.

RESULTS

Eligible Studies

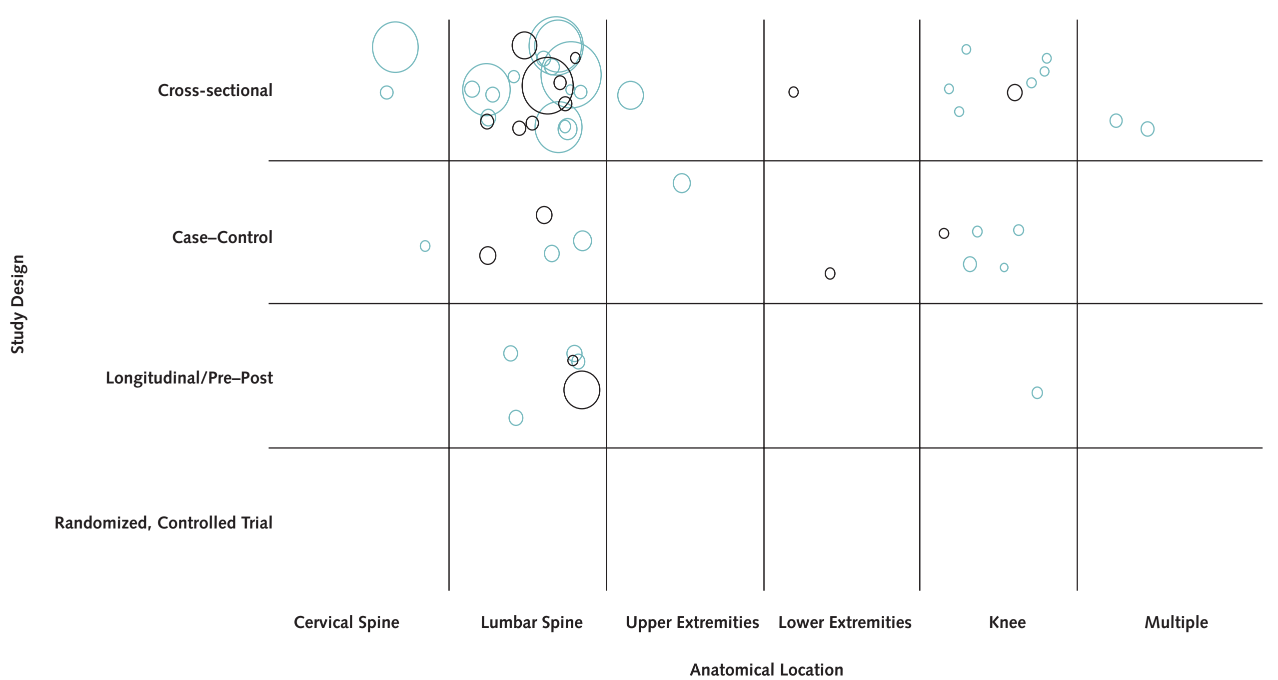
Our MEDLINE search yielded 5984 citations, of which 416 were considered potentially eligible and were retrieved in full text. Full-text articles were screened on the basis of study eligibility criteria, which yielded 55 publications that used MRI with weight-bearing or stress-loading protocols in patients with musculoskeletal conditions (19–73). Of these, 1 article reported data from 2 separate studies (52). We identified 1 additional article by hand-searching reference lists (74). Thus, 57 studies (in 56 publications) were included in the evidence map (**Appendix Figure 1**). **Appendix Figure 2** (available at www.annals.org) shows the study selection process.

Devices, Populations, and Study Designs

We categorized these 57 studies according to the devices being used: 1) open, positional, and weight-bearing MRI scanners (36 studies) (19–52, 73, 74); 2) specialized devices to "simulate" gravity (that is, axial loading) in a conventional MRI scanner (19 studies) (52–70); and 3) other specialized devices to obtain an MRI under stress-loading conditions in a conventional MRI scanner (2 studies) (71, 72). Weight-bearing MRI scanners had low magnetic field strengths (maximum, 0.6-T magnets), whereas those that used axial loading had higher magnetic field strengths (>1 T in 18 of the 19 studies). **Appendix Tables 1** and **2** (available at www.annals.org) summarize the descriptive characteristics of the eligible studies.

All of the studies were published between 1993 and 2010. The most commonly imaged body regions were the lumbar spine (33 studies) and knee (13 studies) (**Figure 2**). Across all studies, the median of the average (mean or median) age of patients with musculoskeletal conditions was 42.6 years (25th, 75th percentile, 31.6, 50.0 years); the median of the mean or median age of control participants (for case–control studies) was substantially lower, at 29.9 years (25th, 75th percentile, 28.0, 34.4 years). Approximately 50% of the participants in the eligible studies were men.

Figure 2. **Map of available evidence, stratified by study design and anatomical location.**



The green circles represent studies and are proportional to the number of enrolled patients; the black circles represent studies that reported diagnostic or patient-relative outcomes and compared at least 2 tests. Placement of studies within each box is random. Two studies did not report sample size and are not shown. Two studies monitoring changes before and minutes after an orthopedic intervention or physical activity are plotted along with longitudinal studies.

In general, studies were small; the median (25th, 75th percentile) number of included case patients was 26 (17, 45), and the median (25th, 75th percentile) number of control participants was 13 (12, 20 for case–control studies only). No randomized, controlled study or nonrandomized comparative study of testing using MRI under loading stress versus no testing was identified.

Most studies were cross-sectional (37 studies) or had case–control designs (13 studies). Only 5 longitudinal studies and 2 studies in which MRI was performed before and minutes after an orthopedic intervention or physical activity ("pre–post" studies) were included. Most studies did not systematically identify case patients or control participants. Fifteen studies (27%) were comparative studies of 2 diagnostic tests and reported diagnostic or patient-relevant outcomes.

Outcomes

Diagnostic or patient-relevant outcomes were assessed infrequently (4 studies evaluated the effect of testing on physician thinking and therapertic decision making). Twenty-seven studies (47%) focused on the feasibility of imaging under weight-bearing or stress-loading conditions (for example, agreement in anatomical measurements among different imaging modalities). Forty-five studies enrolled exclusively symptomatic patients, 7 studies enrolled exclusively asymptomatic patients, and 4 studies enrolled mixed populations; 1 study did not report relevant information.

Only 14 studies assessed accuracy outcomes, defined broadly as the identification of abnormalities in symptomatic patients by using weight-bearing or stress-loading MRI. Two studies addressed patient management or treatment planning, and 2 studies reported on disease monitoring.

Adverse Events

Ten studies reported harms or adverse events associated with weight-bearing MRI testing (**Appendix Table 3**, available at www.annals.org). Common adverse events were new-onset or worsening pain or neuropathy that occurred while the patients were placed under loading stress (weight-bearing or axial-loading). Studies reported test interruption or noncompletion rates of 5% to 10% due to symptoms that developed during loading. The investigators of 1 study amended the study design to evaluate sitting instead of upright MRI because patients could not remain still during the upright examination (25).

Location and Funding Sources

Most studies were conducted outside of the United States. Funding information was often not reported, and studies that reported relevant information frequently stated that no funding was received. Because of the lack of relevant information in a large number of studies and the potential influence of different editorial policies on reporting financial support, interpreting this finding is difficult.

Potential for Patient Population Overlap

Multiple studies originated from the same research centers. In such cases, ascertaining whether studies conducted by the same investigators shared case patients or control participants is often impossible. Twenty publications (35% of eligible studies) were produced by 4 teams. Thus, despite the availability of 57 studies on MRI under loading stress, the effective information size is probably much smaller (75).

Comparative Studies That Reported Diagnostic or Patient Outcomes

Comparative studies that assess the performance of 2 or more diagnostic tests provide information that is applicable to clinical decision making. Of the 57 studies discussed earlier, 15 used at least 2 diagnostic tests and reported diagnostic or patient-relevant outcomes (20, 43, 45–48, 51, 55, 57, 59, 67–70, 72) (**Appendix Table 4**, available at www.annals.org). None of these studies used a gold standard to establish diagnoses. Only 4 studies reported patient-relevant outcomes (pain, anxiety, testing preference, or physical function), and only 1 study reported changes in patient management based on additional information gained from axial-loading MRI.

Four studies of lumbar spine imaging compared open, positional, weight-bearing MRI with conventional MRI (45, 46), myelography (48), or non–weight-bearing imaging in the same MRI device (51). These studies did not report the effect on patient outcomes. Only 1 study assessed patient preferences and anxiety during open, positional MRI and during lumbar myelography and reported that more patients were anxious during myelography than during MRI and that more patients preferred MRI than myelography (48); however, no data were provided on whether diagnosis, treatment, or patient outcomes were affected.

Seven studies of lumbar spine imaging compared axial-loaded images with preloaded images in the same conventional MRI scanner and reported that use of axial-loaded MRI led to additional diagnoses or affected diagnostic thinking (55, 57, 59, 67–70). Five of these 7 studies originated from a single group of investigators in Sweden, and there was obvious patient overlap among some of these publications (55, 67–70). At least 2 of the investigators in this group are the co-inventors of an axial-loading device, DynaWell L-Spine (DynaWell Diagnostics, Las Vegas, Nevada), which is currently commercially available. All 7 studies had potential selection or verification biases.

Two studies of foot imaging that compared weight-bearing MRI with MRI in the supine position by using the same MRI device found that the 2 techniques provided similar information (43, 47). Two studies of imaging of the knee joint compared weight-bearing MRI with non–weight-bearing MRI by using the same MRI device (20, 72). One study included only patients who had a previous diagnosis of meniscal tears by using conventional MRI that were confirmed by arthroscopy reported that patients with displaceable meniscal tears (diagnosed by using weight-bearing MRI) had significantly more pain than patients with nondisplaceable meniscal tears (20). The other study reported that loaded dynamic MRI "missed" fewer patellofemoral joint abnormalities than unloaded dynamic MRI (72). However, no functional outcomes were reported to verify the importance of these imaging findings.

Ongoing Studies

Our search for ongoing clinical trials using weight-bearing or stress-loading MRI identified 3 ongoing studies (ClinicalTrials.gov registration numbers: NCT00665548, NCT00706459, and NCT00887744). Their results are not yet available on the ClinicalTrial.gov Web site, and we could not identify any corresponding publications in MEDLINE. Because the sample size of these studies is small (anticipated enrollment ranged from 33 to 163 participants), their results, once published, are unlikely to change the conclusion of our evidence map.

Discussion

Magnetic resonance imaging under loading stress has been proposed as an approach to improve the clinical utility of musculoskeletal MRI, and stress-loading technologies are marketed directly to consumers for clinical use. The diversity of existing stress-loading applications and the emergence of many competing new technologies are a cause for concern among health professionals and policymakers, particularly in terms of image quality and cost-effectiveness (12).

We reviewed 57 studies published during the past 20 years that investigated different MRI devices that allowed imaging under loading stress. Despite the large number of available studies, considerable uncertainty remains about the utility of this technique for the clinical management of musculoskeletal conditions.

Evaluating the clinical utility of medical tests is challenging. Test results have little direct effect on patient-relevant outcomes; thus, the utility of medical tests is determined by their indirect impact on outcomes by using their influence on physician thinking and therapeutic decision making.

It is often infeasible to conduct overarching studies that assess the overall impact of tests on the clinical management process. Therefore, the evaluation of medical tests often resembles putting together the pieces of a puzzle to appraise the alternative test and treatment options. This evaluation includes the assessment of evidence in the clinical setting where the test is applicable; the role of the test in the clinical management process; and, finally, the effect of the test on clinical outcomes.

The settings in which MRI under loading stress would be indicated are currently unclear; the available studies do not provide information on whether such imaging tests are useful for diagnosis, monitoring treatment response, or treatment planning. The role of MRI under loading stress is to manage musculoskeletal conditions (that is, whether it can be used as a replacement for conventional MRI, an add-on test for diagnostically challenging cases, or a triage test for selecting patients to undergo more invasive imaging) remains similarly uncertain.

The studies that we reviewed rarely assessed patient-relevant outcomes. Studies using MRI under loading stress along with contemporary imaging alternatives rarely reported outcomes other than anatomical measurements with no reference to the utility of the tests in discriminating between affected and unaffected persons. Such studies do not provide adequate evidence to support the superiority (or equivalence) of stress-loading MRI to conventional imaging alternatives. The few studies that did report diagnostic or patient-relevant outcomes included heterogeneous patient populations, demonstrated diverse outcomes, and did not permit conclusions based on the comparative performance of tests.

Furthermore, studies had several methodological limitations, such as small sample sizes, lack of reporting on diagnostic accuracy measures, susceptibility to spectrum bias due to the use of case–control designs (76), and lack of a gold standard for establishing diagnoses. Previous literature surveys suggest that many of these limitations are prevalent in the orthopedics and MRI literature (77, 78). Another key issue that the available studies did not adequately address was the potential effect of low magnetic field strength (<1 T) on the image quality of weight-bearing (upright) MRI devices.

Our observations are consistent with a 2007 technology assessment that did not identify adequate data to determine the diagnostic validity or accuracy for upright, multipositional MRI scanners (12). Our findings emphasize the need to improve the information on diagnostic utility of MRI under loading stress but also highlight the complexities of bringing imaging modalities with uncertain clinical utility into clinical practice. Taking into account past trends in the growth of MRI in the United States (79) and the large number of studies that we reviewed, further increases in the use of stress-loading MRI should be expected in the future.

The FDA considers the commercially available stress-loading MRI scanners that we reviewed to be "substantially equivalent" to conventional MRI devices. However, we argue that further validation of their diagnostic accuracy and clinical utility is necessary because of the potential implications of an incorrect diagnosis. Both false-positive and false-negative results may have serious consequences, such as suggesting surgery or other treatments for musculoskeletal conditions when they are unnecessary or delaying treatment when it is needed. Current practice guidelines do not recommend the use of these devices, and most public and private payers consider MRI under loading stress to be an experimental procedure (80).

Future research on emerging MRI technologies under loading stress should address the methodological issues in study design and analysis that are prevalent in the existing literature so that studies can better evaluate the reliability and diagnostic accuracy of novel MRI technologies. This research would allow a reliable assessment of the effect of stress-loading MRI technologies on diagnostic thinking and therapeutic decision making. The effect of the most promising test strategies on patient outcomes can then be assessed by using prospective observational studies or randomized, controlled trials.

In conclusion, our review of the literature suggests that MRI under stress loading is an area of active research. Currently available devices allow imaging under stress either by simulating gravity by using axial loading or allowing imaging in nonrecumbent positions. Although these imaging modalities are currently marketed directly to consumers as an alternative to conventional MRI devices, the evidence base underlying claims of equivalence or superiority compared with conventional MRI scanners is limited.

In summary, our findings suggest that research on stress-loading MRI is at an early developmental stage, with most studies focusing on non–clinically relevant end points. Until additional research becomes available, MRI under stress loading should probably be considered experimental except when MRI is considered necessary and specific circumstances preclude the use of conventional devices.

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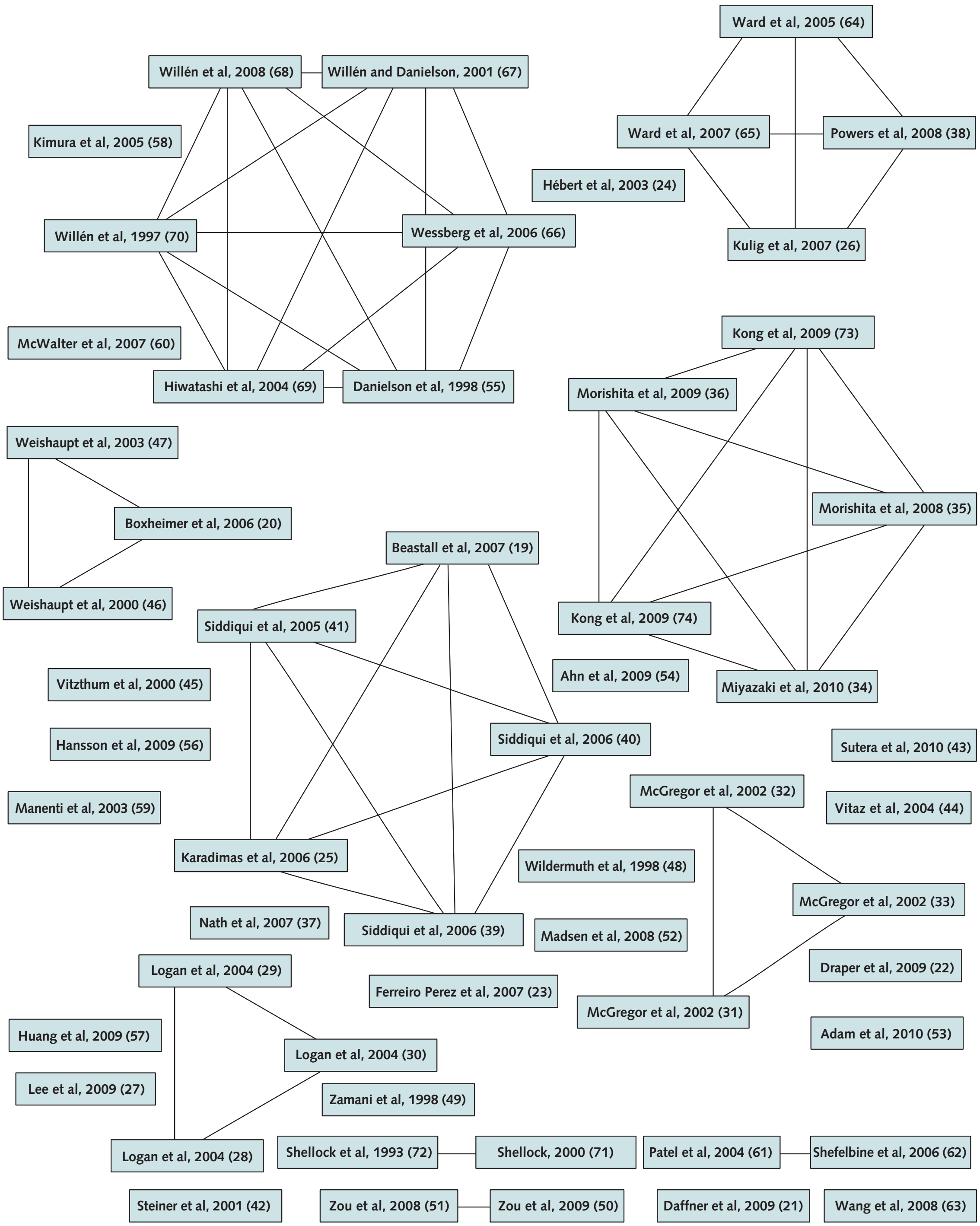
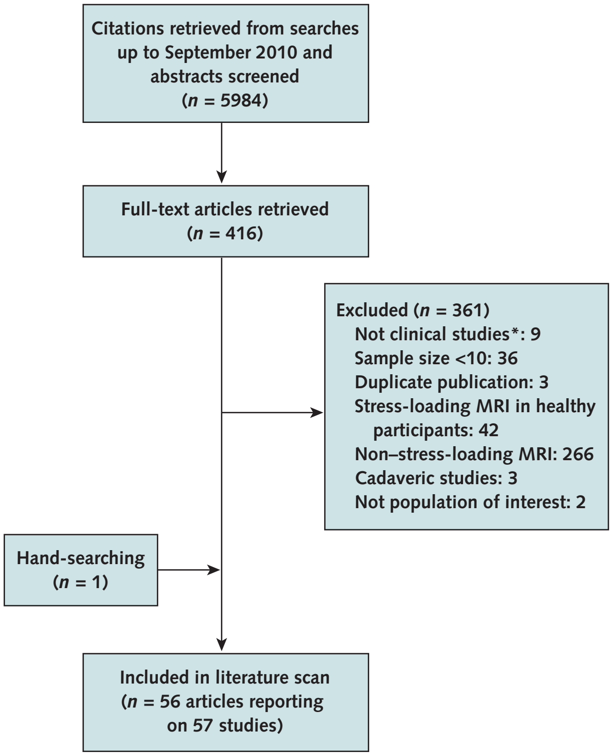
Administrative, technical, or logistic support: M. Chung.
Collection and assembly of data: I.J. Dahabreh, N. Hadar, M. Chung.

Appendix Figure 1. **Evidence map of shared authorship patterns in studies of stress-loading magnetic resonance imaging.**



This figure shows that 32 teams of investigators produced 56 publications that reported on 57 studies. It does not necessarily imply overlap of patient populations but represents a method to identify the most active research groups in the field by showing overlap among author lists in included studies. Each publication is represented by a box, and studies that share at least 1 author are shown as a group of boxes linked with lines. The Methods section describes how the figure was generated. One team that published 6 articles, which constitute approximately 10% of all of the studies that we considered eligible, included Drs. Danielson and Willén (inventors of the DynaWell axial-loading MRI device [DynaWell Diagnostics, Las Vegas, Nevada]) as coauthors.

Appendix Figure 2. **Summary of evidence search and selection.**



MRI = magnetic resonance imaging.
* Reviews, letters, or editorials.

Appendix Table 1. **Patient Characteristics in the Included Studies***

Characteristic	All Studies (*n* = 57)	Open, Positional, and Weight-Bearing† MRI (*n* = 36)	Conventional MRI With Specialized Devices to Simulate Gravity (*n* = 19)
Enrollment			
Median number of case patients (25th, 75th percentile; minimum, maximum)	26 (17, 45; 8, 553)	30 (20, 50; 10, 553)	24 (12, 34; 8, 250)
Median number of control participants (25th, 75th percentile; minimum, maximum)‡	13 (12, 20; 5, 50)	13 (12, 20; 10, 50)	14 (13, 18; 10, 43)
Men, *n*			
Median (25th, 75th percentile) case patients	51 (40, 63)	54 (43, 67)	45 (19, 53)
Median (25th, 75th percentile) control participants‡	53 (20, 65)	58 (40, 70)	NA§
Mean or median age‖			
Case patients (25th, 75th percentile), *y*	42.6 (31.6, 50.0)	41.9 (32.0, 44.5)	48.0 (27.1, 52.0)
Case patients ≥65 y, *n (%)*	3 (5)	2 (6)	1 (6)
Control participants (25th, 75th percentile), *y*	29.9 (28.0, 34.4)	32.1 (26.8, 34.4)	28.4 (28.1, 36.3)
Control participants ≥65 y, *n (%)*‡	0 (0)	0 (0)	0 (0)
Health status of enrolled patients, *n (%)*			
Exclusively symptomatic	45 (79)	31 (86)	13 (68)
Asymptomatic	7 (12)	2 (6)	4 (21)
Mixed or not reported	5 (9)	3 (8)	2 (11)
Country, *n (%)*			
United States	18 (32)	11 (31)	5 (26)
Outside the United States	35 (61)	21 (58)	14 (74)
Mixed	4 (7)	4 (11)	0 (0)

MRI = magnetic resonance imaging; NA = not applicable.
* Numbers represent studies (percentage of total studies in each category), unless otherwise stated. Percentages have been rounded to the nearest integer and may not sum to 100%.
† Because only 2 studies assessed MRI under weight-bearing conditions in a closed MRI scanner, we did not include a separate column for this group of studies.
‡ Only applicable to case–control studies.
§ Only 2 studies provided information.
‖ Only among studies that reported relevant information.

Appendix Table 2. **Design Characteristics of the Included Studies***

Characteristic	All Studies (*n* = 57)	Open, Positional, and Weight-Bearing† MRI (*n* = 36)	Conventional MRI With Specialized Devices to Simulate Gravity (*n* = 19)
Funding source reported, *n* (%)			
Yes	36 (63)	20 (56)	14 (74)
No	21 (37)	16 (44)	5 (26)
Industry funding, *n* (%)‡			
Yes	11 (31)	3 (15)	6 (43)
No§	25 (69)	17 (85)	8 (57)
Study design, *n* (%)			
Cross-sectional	37 (65)	24 (67)	13 (68)
Case–control	13 (23)	7 (19)	5 (26)
Crossover	0 (0)	0 (0)	0 (0)
Longitudinal	5 (9)	4 (11)	1 (5)
Before and minutes after an orthopedic intervention or physical activity	2 (4)	1 (3)	0 (0)
Nonrandomized comparative	0 (0)	0 (0)	0 (0)
Timing of follow-up, *n* (%)			
Prospective	5 (9)	5 (14)	0 (0)
Retrospective	1 (2)	0 (0)	1 (5)
NA‖	48 (84)	30 (83)	16 (84)
Unclear	3 (5)	1 (3)	2 (11)
Number of centers, *n* (%)			
Multicenter	4 (7)	3 (8)	1 (5)
Single-center	39 (68)	22 (61)	15 (79)
Unclear or not reported	14 (25)	11 (31)	3 (16)
Clinical setting, *n* (%)			
Feasibility	27 (47)	18 (50)	9 (47)
Screening	1 (2)	0 (0)	1 (5)
Diagnosis	15 (26)	9 (25)	6 (32)
Prognosis or prediction	1 (2)	0 (0)	0 (0)
Patient management or treatment planning	1 (2)	0 (0)	1 (5)
Monitoring	2 (4)	2 (6)	0 (0)
Multiple or unclear	10 (18)	7 (19)	2 (11)
Anatomical region of MRI, *n* (%)			
Cervical spine	3 (5)	2 (6)	1 (5)
Lumbar spine	33 (58)	20 (56)	13 (68)
Knee	13 (23)	6 (17)	5 (26)
Upper extremities	2 (4)	2 (6)	0 (0)
Lower extremities (other than knee)	2 (4)	2 (6)	0 (0)
Multiple regions	4 (7)	4 (11)	0 (0)
Reported adverse events, *n* (%)			
Yes	10 (18)	5 (14)	5 (31)
No	47 (82)	31 (86)	14 (74)
Outcomes assessed, *n* (%)			
Accuracy	14 (25)	9 (25)	4 (21)
Effect on diagnostic thinking	3 (5)	2 (6)	1 (5)
Effect on treatment decisions	1 (2)	0 (0)	1 (5)
Effect on patients' functional and clinical outcomes	1 (2)	0 (0)	0 (0)
Anatomical measurements, rater agreement, other, or mixed	38 (67)	25 (69)	13 (68)

MRI = magnetic resonance imaging; NA = not applicable.
* Data are presented as the number of studies (percentage of total studies in each category), unless otherwise stated. Percentages have been rounded to the nearest integer and may not sum to 100%.
† Because only 2 studies assessed MRI under weight-bearing conditions in a closed MRI scanner, we did not include a separate column for this group of studies.
‡ Only among studies that reported funding sources.
§ Most studies in this category reported that "no funding was received."
‖ Case–control or cross-sectional studies.

Appendix Table 3. **Studies of Weight-Bearing or Stress-Loading MRI Reporting on Adverse Events***

Study, Year (Reference)	Patients, *n*	Imaging Method	Adverse Events or Safety Outcomes
Danielson et al, 1998 (55)	34	Axial-loading	Twenty patients (59%) experienced symptoms during MRI with axial loading. Of those, 7 (21%) had low back pain and 10 (29%) had leg pain. Two patients (6%) had low back pain, both in the psoas-relaxed and axial-loading positions; 1 of these patients (3%) had leg pain in the axial-loading position. One patient (3%) had no low back pain but had sensory disturbance.
Weishaupt et al, 2000 (46)	36	Weight-bearing MRI	MRI could not be completed because of severe pain in 6 patients (17%).
Hébert et al, 2003 (24)	41	Weight-bearing MRI	None
Kimura et al, 2005 (58)	12	Axial-loading	One control participant (6%) did not undergo imaging because axial loading caused radicular pain.
Karadimas et al, 2006 (25)	30	Weight-bearing MRI	Upright MRI was attempted, but patients had difficulty standing still. All imaging was obtained in a neutral sitting position.
Madsen et al, 2008 (52)	16	Axial-loading	Two patients (13%) did not complete the last scan because of discomfort.
Wang et al, 2008 (63)	27	Axial-loading	Two patients (7%) did not complete the loaded test because of pain induced by loading.
Morishita et al, 2008 (35)	NR	Weight-bearing MRI	"Some" patients needed pain control before MRI because of severe discogenic or radicular pain in upright, weight-bearing positions. The position was difficult to maintain for more than 30 min.
Huang et al, 2009 (57)	32	Axial-loading	Three patients (9%) could not complete the axial-loaded examination because of pain ($n = 1$) or sciatica and numbness ($n = 2$). In 1 patient (3%), sciatica and numbness persisted after axial-loading; an electrophysiologic study revealed lumbosacral radiculopathy.
Ahn et al, 2009 (54)	51	Axial-loading	Ten percent of patients did not complete axial-loading imaging because of back pain or sciatic pain.

MRI = magnetic resonance imaging; NR = not reported.
* The studies included in this table were those that reported on the incidence of adverse events (including "no adverse event").

Appendix Table 4. **Studies Directly Comparing Diagnostic Tests and Reporting on Clinical, Diagnostic, or Patient-Relevant Outcomes**

Study, Year (Reference)	Location; Number of Study Centers; Enrollment Period	Number of Participants Enrolled; Inclusion Criteria; Sampling	Mean Age, y*	Men, %	MRI Characteristics†		Main Findings	Funding Source and Other Comments
					Weight-Bearing MRI	Comparator		
Lumbar spine								
Open, positional MRI								
Vitzthum et al, 2000 (45)	Germany; NR; NR	50 case patients and 50 control participants; case patients had lumbar disc herniation (82%), lateral osteogenic recess stenosis (10%); degenerative spondylolisthesis (8%), and control participants were healthy volunteers; sampling not described	Case patients: 53 (34–71) Control participants: 24.5 (3.4)	Case patients: 60 Control participants: 56	Open, interventional MRI; Signa SP (GE); 0.5 T; sitting; neutral, extension, flexion, rotation (dynamic); vertically open	Prior MRI findings: decompression of the lumbar nerve roots, which correlated with clinical symptoms	In 32 (64%) patients, dynamic flexion-extension examination contributed important additional information to the preliminary diagnosis.; patients had characteristics of a type I functional pattern	Nonindustry only
Weishaupt et al, 2000 (46)	Switzerland; single-center; NR	36 (30 analyzed); recruited after lumbar spine MRI and had had low back pain or leg pain for >6 weeks, were unresponsive to a trial of nonsurgical treatment, surgery was not indicated or not urgent on the basis of clinical findings; sampling not described	38 (20–50)	57	Open, interventional MRI; positional MRI; Signa Advanced SP (GE); 0.5 T; sitting; extension, flexion (static); vertically open	cMRI; Impact Expert (Siemens); 1.0 T; no loading; supine neutral; closed	Diagnoses in supine position (cMRI) changed in 4 disks (5%) in seated flexion and in 7 disks (9%) in seated extension; positional pain differences are related to position-dependent changes in foraminal size	NR
Wildermuth et al, 1998 (48)	Switzerland; single-center; NR	30; patients referred for lumbar myelography and agreeing to undergo MRI with an open system in another institute; consecutive sampling	58 (27–84)	43	Open, interventional MRI; Advantage SP (GE); 0.5 T; sitting; extension, flexion (static); vertically open	Lumbar myelography; radiographs were obtained with fluoroscopic guidance in the lateral decubitus, prone, and left and right posteroanterior oblique projections.; upright anteroposterior and lateral images were then obtained at flexion and extension	More patients reported anxiety during myelography than during MRI, and more patients preferred MRI to myelography; myelography and positional MRI were comparable for quantitative assessment of sagittal dural sac diameters	Nonindustry only; 17% patients could not be contacted for preferences and anxiety outcomes
Zou et al, 2008 (51)	United States; NR; 2005–2006	533; patients with symptomatic back pain ± radiculopathy; selection criteria and sampling not described	46.2 (18–76)	42	Kinetic, upright MRI in extension or flexion position; upright multiposition MRI; upright (FONAR); 0.6 T; standing ; extension, flexion (static); vertically open	Kinetic, upright MRI in neutral position; Upright multiposition MRI; Upright (Fonar); 0.6 T; standing ; neutral; vertically open	19.4%, 13.3% 10.6%, and 9.1% "missed diagnosis" of disc herniation in patients with grade 1 (0–3 mm), grade 2 (3–5 mm), grade 3 (5–7 mm), and grade 4 (7–9 mm) lumbar disc bulges, respectively	Nonindustry only; missed diagnosis rates were calculated based on the number of lumbar discs (not patients)
Axial-loading MRI								
Danielson et al, 1998 (55)	Sweden; single-center; 1994–1996	34; clinically suspected lumbar spinal canal narrowing causing sciatica or neurogenic claudication; sampling not described	50 (25–71)	53	cMRI with axial loading; cMRI with axial loading; Magnetom Impact (Siemens); 1.0 T; custom-made axial loading compression device (300–400 N or ~50% BW); axial loading of the lumbar spine in extension; closed	Preloaded cMRI ; cMRI before axial loading; Magnetom Impact (Siemens); 1.0 T; no loading; PRP; closed	7 patients (21%) had low back pain and 10 (29%) had leg pain in axial loading of the lumbar spine in extension; 1 recess stenosis was found in 12 patients, and foraminal stenosis was seen in 1 patient; 5 patients with leg pain during axial loading had a disc herniation, and 6 had a recess stenosis	Industry; post-hoc exclusion of patients from most of the analyses; on the basis of enrollment years and data presented in the table, patients overlapped with other publications from the same group (references 67 and 70)

Continued on following page

Appendix Table 4—**Continued**

Study, Year (Reference)	Location; Number of Study Centers; Enrollment Period	Number of Participants Enrolled; Inclusion Criteria; Sampling	Mean Age, *y**	Men, %	MRI Characteristics†		Main Findings	Funding Source and Other Comments
					Weight-Bearing MRI	Comparator		
Hiwatashi et al, 2004 (69)	Sweden; single-center; NR	20; patients with signs and symptoms of spinal stenosis with detected appreciable difference in the caliber of the dural sac on routine and axial-loading MRI; sampling not described	54 (32–75)	70	cMRI with axial loading; device model NR; 1.0 T; DynaWell L-Spine, 50% BW; axial loading of the lumbar spine in extension; closed	Preloaded cMRI; cMRI before axial loading; device model NR; 1.0 T; no loading; PRP; closed	Additional information gained from axial loading during MRI of the lumbar portion of the spine changed neurosurgeons' treatment decision from conservative management to decompressive surgery for 5 (25%) patients	Funding source NR; retrospective secondary database analyses; patient selection was based on MRI findings
Huang et al, 2009 (57)	Taiwan; NR; NR	32 (29 analyzed); patients with degenerative L4–L5 spondylolisthesis, grade 1 or 2 slippage were included, and those with degenerative scoliosis were excluded; consecutive sampling	NR	19	cMRI with axial loading; Signa Cvi (Siemens); 1.5 T; DynaWell, 50% BW; supine in extension; closed	Preloaded cMRI; Signa Cvi (Siemens); 1.5 T; no loading; supine; closed	After adjustment for sex and age, significant correlations were found between physical functioning and the difference of segmental angulation ($P = 0.01$), ODI and the difference of segmental angulation ($P = 0.04$), and physical functioning and the postloaded lumbar lordotic angles ($P = 0.02$)	Nonindustry only; patients were excluded from the study after axial loading owing to intolerable back pain, numbness, or sciatica
Manenti et al, 2003 (59)	Italy; NR; NR	50 case patients and 43 control participants; case patients had a history of chronic lumbar pain and recurrent movement-induced painful blockages; and control participants were healthy individuals selected by matching on weight, age, sex, and occupation; sampling not described	Case patients: 46 (19) Control participants: matched for age, sex, and occupation	56	cMRI with axial loading; axial-loading MRI; Gyroscan Intera (Phillips); 1.5 T; axial compressor (MIKAI Manufacturing): 65% BW; supine in extension; closed	Preloaded cMRI; neutral unloaded routine MRI; Gyroscan Intera (Phillips); 1.5 T; no loading; PRP; closed	43 case patients were studied for a total of 129 disc levels; 31 presented with disc degeneration at 56 (43%) of the studied disc levels; Disc protrusion was found at 19 disc levels in 12 patients	Nonindustry only
Willén et al, 1997 (70)	Sweden; single-center; 1994–1995	34 (80 anatomical sites); patient selection criteria not described; sampling not described	53 (25–74)	53	cMRI with axial loading; Magnetom Impact (Siemens); 1.0 T; custom-made axial-loading harness (~50% BW); axial loading of the lumbar spine in extension; closed	Preloaded cMRI; cMRI before axial loading; Magnetom Impact (Siemens); 1.0 T; no loading; PRP; closed	Stenosis was found in 11 patients (16 sites); narrowing of the lateral recess was noted at 13 sites	NR; post hoc exclusion of patients from most of the analyses; on the basis of enrollment years and data presented in the table, patients overlapped with subsequent publications from the same group of investigators (reference 67)
Willén and Danielson, 2001 (67)	Sweden; single-center; 1994–1998	122; patients with low back pain, sciatica, or neurogenic claudication; sampling not described	50 (14–80)	52	cMRI with axial loading; cMRI with axial loading; Magnetom Impact (Siemens); 1.0 T; DynaWell L-Spine, 40% BW (never >50% BW); axial loading of the lumbar spine in extension; closed	Preloaded cMRI; protocol same as that in reference 70	"Additional valuable information" was found by axial-loading MRI in 29% of patients (all findings were in patients with sciatica or neurogenic claudication); No additional valuable information was found in patients with low back pain	Industry; post hoc exclusion of patients from most of the analyses; on the basis of enrollment years and data presented in the table, patients overlapped with a prior publication from the same group of investigators (reference 70)
Willén et al, 2008 (68)	Sweden; single-center; 1996–2002	250; patients with clinical signs of neurogenic claudication and/or sciatica; sampling not described	NR	NR	cMRI with axial loading; device model NR; 1.0 T; DynaWell L-Spine, 40% BW (never >50% BW); axial loading of the lumbar supine in extension; closed	Preloaded cMRI; protocol same as that in references 67 and 70	In 24 patients, axial loading revealed a "hidden" stenosis in 1 to 3 disc levels, whereas no stenosis was detected with the unloaded examination; 1–6 y after surgery the majority of patients had much improved or improved leg or back pain and subjective walking ability	Industry; outcome data were from the Swedish Spine Register 2005; on the basis of enrollment years and data presented in a table, patients overlapped with prior publications from the same group of investigators (reference 67)

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Appendix Table 4—Continued

Study, Year (Reference)	Location; Number of Study Centers; Enrollment Period	Number of Participants Enrolled; Inclusion Criteria; Sampling	Mean Age, y*	Men, %	MRI Characteristics†		Main Findings	Funding Source and Other Comments
					Weight-Bearing MRI	Comparator		
Knee								
Boxheimer et al, 2006 (20)	Switzerland; single-center; 2002–2003	42; patients suspected of having a meniscal tear, and diagnosis of meniscal tears on the basis of cMRI and confirmed by arthroscopy; sampling not described	37 (18–60)	71	Open, interventional MRI; kinematic MRI; Signa SP (GE); 0.5 T; flexible transmit-receive surface coil; standing (allowing arms on a support frame); upright; vertically open	Supine position in open, interventional MRI; kinematic MRI; Signa SP (GE); 0.5 T; flexible transmit–receive surface coil; no loading; supine, or supine 90° flexion with rotation; vertically open	58% of menisci with tears did not reveal any displacement between the different knee positions; patients with displaceable meniscal tears reported significantly more pain in all 3 knee positions than did patients with nondisplaceable meniscal tear ($P < 0.05$)	NR
Shellock et al, 1993 (72)	United States; single-center; NR	17 case patients and 5 control participants; case patients had a provisional clinical diagnosis of abnormal patellar alignment and tracking, and selection of control participants was not described; sampling not described	Case patients: 31 (17–48) Control participants: NR	Case patients: 39 Control participants: 39	cMRI with kinetic resistance loading; 64-MHz imager; device model NR; 1.5 T; nonferromagnetic positioning device with a force of 30 ft-lb/s (resistance); Prone position with joints movement from ~45° to extension; closed	cMRI without loading; 64-MHz imager; device model NR; 1.5 T; nonferromagnetic positioning device without load; Prone position with joints movement from ~45° to extension; closed	Unloaded kinematic MRI was normal in 41% of symptomatic patients, and loaded kinematic MRI was normal in 5.9%; the severity of abnormalities was qualitatively the same with both techniques (9 cases) or greater with the loaded technique (7 cases)	Industry
Foot								
Sutera et al, 2010 (43)	Italy; single-center; 2009	20 case patients and 20 controls; case patients had a clinical diagnosis of clinical diagnosis of plantar fasciitis, and control participants were healthy volunteers; convenience sampling	Case patients: 36 (24–45) Control participants: 33 (20–41)	Case patients: 80 Control participants: 70	Tilting MRI in upright position; dedicated upright MRI; G scan (Esaote); 0.25 T; standing (~82°); neutral; laterally open	Tilting MRI in supine position; Dedicated upright MRI; G scan (Esaote); 0.25 T; conventional supine; neutral; laterally open	Both supine and upright positions enabled identification of plantar fasciitis in 15 of 20 case patients (75%); no control participant had plantar fasciitis or abnormal MRI findings in the upright or supine position	Nonindustry only
Weishaupt et al, 2003 (47)	Switzerland; single-center; 2000–2001	18; patients suspected of having Morton neuroma underwent cMRI of their symptomatic forefoot in the prone position, and only those who had >1 Morton neuroma that was 5 mm or larger in its transverse diameter were included; referred by foot surgeons or orthopedic foot surgeons	50 (25–72)	6	Weight-bearing MRI; Signa Advanced SP (GE); 0.5 T; sitting; extension, flexion (static); vertically open	cMRI; Impact Expert (Siemens); 1.0 T; no loading; prone position; closed; supine MRI in open scanner Supine MRI; Signa Advanced SP (GE); 0.5 T; no loading; supine; vertically open	No additional Morton neuroma was found on any of the images; visibility of Morton neuroma was significantly better with cMRI in the prone position than in the supine position	NR; only included patients with successful imaging by all three tests, with Morton neuroma in the prone position

BW = body weight; cMRI = conventional magnetic resonance imaging; MRI = magnetic resonance imaging; NR = not reported; ODI = Oswestry Disability Index; PRP = psoas-relaxed position.
* Data in parentheses are SDs or ranges.
† MRI characteristics are reported as device description; model (manufacturer); field strength; loading; positioning; and configuration. Manufacturer locations are as follows: DynaWell Diagnostics, Las Vegas, Nevada; Esaote, Genoa, Italy; GE Healthcare, Chalfont St. Giles, United Kingdom; FONAR, Melville, New York; MIKAI Manufacturing, Genoa, Italy; Phillips, Best, the Netherlands; Siemens Healthcare, Malvern, Pennsylvania.