Proactive Ergonomic Design for Interventional MRI: Insights from Digital Human Modeling

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Abstract

Interventional MRI (iMRI) is increasingly recognized as a powerful platform for image-guided procedures, offering non-ionizing imaging and superior soft-tissue contrast compared with conventional CT-guided workflows [1, 2]. While the clinical benefits of iMRI are well established, less attention has been paid to the physical and ergonomic demands placed on interventional radiologists who must work within the geometric constraints of MRI systems. Longer bore lengths, narrower access, and constrained reach conditions can require clinicians to adopt sustained, non-neutral postures that may elevate musculoskeletal loading over time.

The solution is to apply digital human modeling (DHM) techniques to quantify ergonomic exposures during simulated needle-insertion tasks performed in CT and MRI environments. By integrating live human motion-capture data with predictive biomechanical simulation, this study demonstrates how scanner geometry, specifically bore length, bore diameter, bore flaring, and table height, interact with clinician anthropometry to influence physical (ergonomic) demands on the body.

The findings show that ergonomic risk in iMRI is not inherent to MRI as a modality but rather is highly design dependent. Certain MRI configurations, particularly those incorporating flared bore entries and elevated table heights, can substantially reduce low-back loading compared with both CT-guided workflows and more conventional MRI designs. Shoulder loading, often cited as a barrier to MRI-guided intervention, was found to be comparatively modest across systems and sensitive to access geometry rather than bore length alone.

This work underscores the value of embedding ergonomics early in scanner design and service planning. Digital human modeling provides a rigorous, evidence-based approach for proactively evaluating human–system interactions. It thereby supports the development of iMRI environments that optimize clinical performance while safeguarding the long-term occupational health of interventional radiologists.

Introduction

Interventional radiology has evolved around the principle of minimally invasive, image-guided therapy, with precision and safety as core objectives. MRI-guided interventions align strongly with these goals, offering real-time visualization without ionizing radiation exposure [3, 4]. Compared with CT guidance, MRI provides superior soft-tissue contrast, which can improve visualization of small

1 Motion-capture data were collected around the MAGNETOM Free.Max* as clinicians performed a simulated needle insertion using a torso phantom to parameterize and validate the digital human model.
** The MAGNETOM Free.Max would not normally be used for interventions. It was used here due to its greater in-bore access and availability.*

The products/features mentioned herein are not commercially available in all countries.Their future availability cannot be guaranteed.

lesions (< 1 cm) and targeting accuracy, particularly in complex anatomical regions [5].

As iMRI adoption increases, clinicians are spending more time performing procedures within MRI environments. Unlike CT scanners, which typically have short gantries and open access, MRI systems are characterized by longer bores and more restrictive entry geometries. To access targets that are positioned near the scanner isocenter, which is required for optimal image quality, interventional radiologists may need to reach deep into the bore while maintaining visual attention on external displays. These constraints shape the posture, reach strategy, and loading at the shoulder and low back, which can influence the risk of developing musculoskeletal disorders.

Why ergonomics matters in image-guided interventions
Musculoskeletal disorders are prevalent among interventional clinicians, with the shoulder and low back frequently identified as regions of vulnerability [2]. Tasks involving sustained arm elevation, asymmetric reaching, and trunk flexion are known to increase joint loading and fatigue potential [6]. In CT-guided procedures, these demands are compounded by the requirement to wear protective lead aprons, which typically add 4–5 kg of mass to the torso and increase spinal loading [7].

MRI-guided interventions eliminate ionizing radiation exposure and therefore the need for lead protection, offering an immediate ergonomic advantage. However, this benefit may be partially offset by the increased reach distances and constrained access imposed by MRI bore geometry and isocenter location. The net ergonomic outcome is therefore not obvious and cannot be inferred from imaging modality alone. Instead, it emerges from the interaction between human characteristics, task demands, and system design.

Digital human modeling provides a computational framework for representing human posture, movement, and biomechanical loading across a range of anthropometries. Modern digital human models can be integrated with computer-aided design (CAD) environments to simulate realistic human–system interactions and quantify joint torques, reach feasibility, and fatigue-related metrics [8, 9]. In this study, DHM was deployed to understand how scanner design elements shape the posture, reach strategy, and loading at the shoulder and low back.

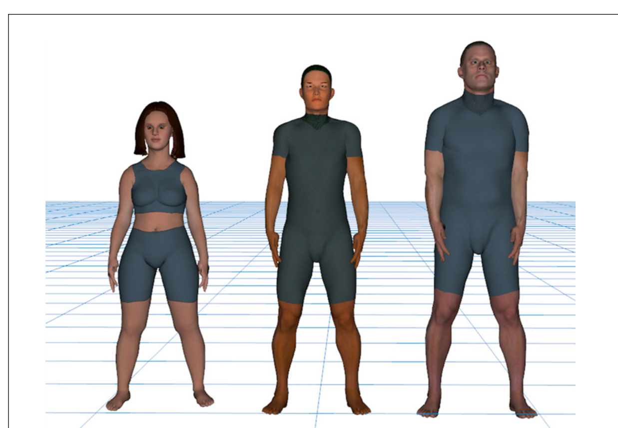
Methodology

Phase 1: From motion capture to comparative simulation
The research followed a two-stage workflow. In the first stage, six clinicians with a range of experience levels and body sizes performed representative needle-insertion tasks in an MRI environment using a torso phantom. Tasks varied by reach depth (isocenter and 12 cm short of the isocenter) and needle orientation, reflecting common interventional scenarios. Whole-body kinematics were captured using an inertial measurement system (Fig. 1) and processed to define a representative "standard" posture.

The MAGNETOM Free.Max would not normally be used for interventions but was used due for greater in-bore access and availability. At the time of the study, the MAGNETOM Free.XL was not yet commercially available; therefore, clinician postures were collected using the MAGNETOM Free.Max during the first phase of the study. These experimentally captured postures were used to inform and calibrate the DHM workflow by providing representative reference postures for simulated needle insertion tasks. From these baseline postures, the DHM could then adapt the simulated clinician's anthropometry to the surrounding MRI geometry in order to predict likely working postures in other scanner configurations, including the MAGNETOM Free.XL. This approach allowed the model to be used to investigate the potential ergonomic implications of different MRI design features within the MAGNETOM Free.XL geometry.

Motion-capture data were used to parameterize and validate the DHM. DHM predicted joint angles for key degrees of freedom fell largely within one standard deviation of the in vivo measured means, indicating that the simulated postures were realistic representations of clinician behavior.

Phase 2: Comparative simulation to inform scanner design
In the second stage, the validated model was applied to comparative simulations of three imaging systems. One was a conventional CT scanner (including simulated lead apron loading) and two were MRI designs with distinct

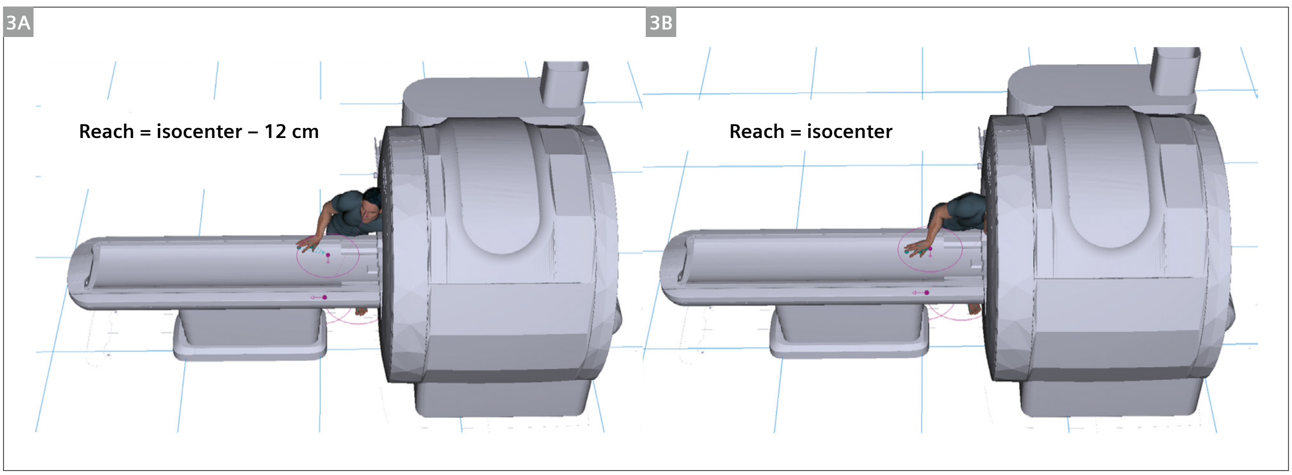


2 Avatars of a woman in the 5th percentile for height, a man in the 50th percentile, and a man in the 95th percentile were selected to understand how clinician anthropometry interacts with MR scanner design elements.

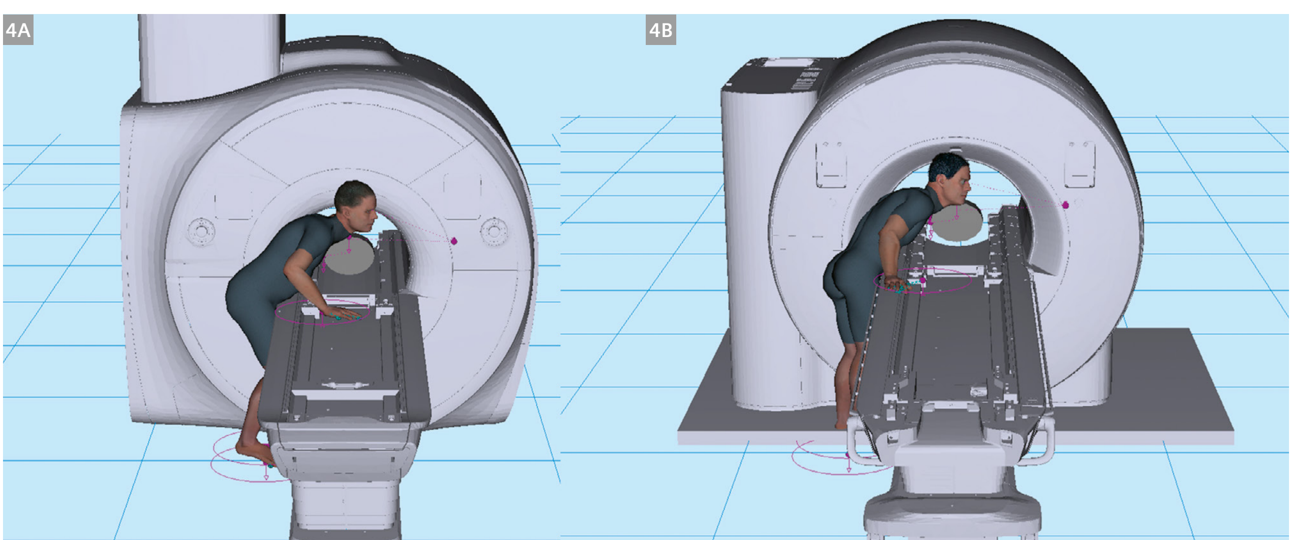
bore geometries: The 0.55T MAGNETOM Free.XL features a 100 cm flared bore design with a larger bore diameter (80 cm) and longer bore length (165 cm) than the 1.5T MAGNETOM Sola, which features no flaring, a smaller bore diameter (70 cm), and a shorter bore length (157 cm). The MAGNETOM Free.XL has a bore geometry specifically designed for interventions, whereas the MAGNETOM Sola represents a conventional MRI scanner.

Avatars representing a woman in the 5th percentile for height, a man in the 50th percentile for height, and man in the 95th percentile for height (Fig. 2) were used to explicitly examine the interaction between scanner design and anthropometry (Fig. 3).

Primary outcome metrics included joint torques at the shoulder and low back, as well as endurance times estimated using joint-specific fatigue models [10]. Joint torques serve as a metric to evaluate the intensity of effort on the shoulder and low back. Endurance time serves as a proxy measure for muscular fatigue, where muscular fatigue is difficult to model directly.



3 Simulation of a male clinician in the 50th percentile for height reaching into the bore to perform a needle ablation. The left panel **(3A)** illustrates a reach to a location that is 12 cm short of the isocenter (the maximum distance from isocenter that can provide strong contrast. The right panel **(3B)** illustrates a reach to isocenter.



4 Bore height, diameter, and flare all influence the ways clinicians will move to perform needle targeting. The left panel **(4A)** illustrates a man in the 95th percentile for height reaching into a scanner with a lower height, narrower bore, and limited flare at bore entry. These design elements can limit the clinician's ability to lean into the bore. The right panel **(4B)** illustrates a man in the 95th percentile for height reaching into a scanner with a higher height, wider bore, and more pronounced flare at bore entry. This enables an easier lean into the bore and a more upright posture while monitoring the screen.

Results

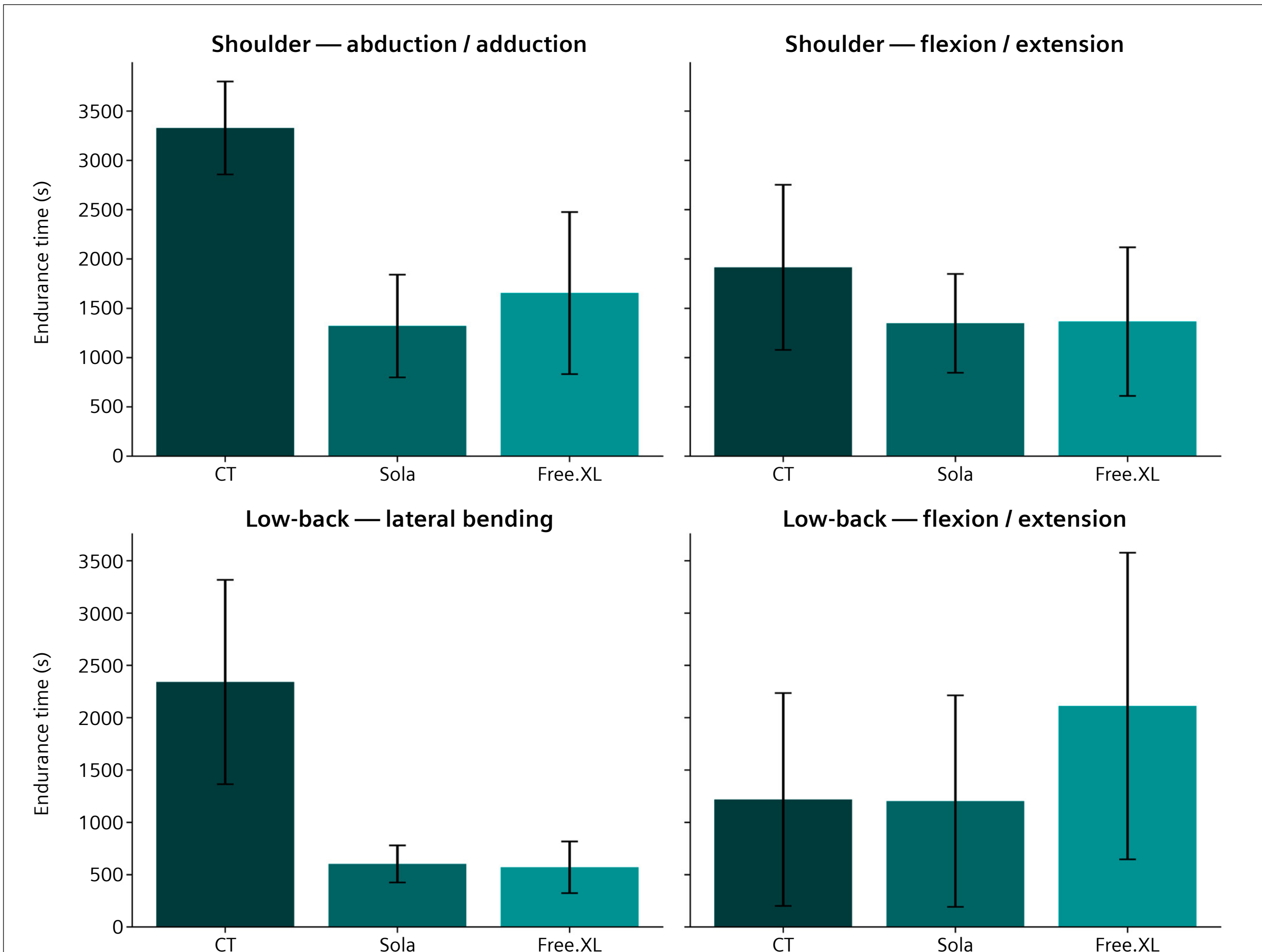
Key findings I: Shoulder loading is modest and geometry dependent

Across all simulated systems, shoulder torques during needle-insertion tasks were relatively low, remaining below levels typically associated with elevated injury risk [6]. As expected, CT-based simulations exhibited the lowest shoulder torques overall, reflecting the shorter reach distances enabled by the compact gantry geometry.

Differences between the two MRI designs revealed important trade-offs. One configuration reduced shoulder abduction/adduction torque while increasing flexion/extension torque, whereas the other demonstrated the opposite pattern. These findings indicate that shoulder loading is influenced not only by bore length, but also by bore diameter, entry flaring, and table height. The 100 cm flared bore of the MAGNETOM Free.XL allows clinicians to position the shoulder closer to the target, reducing moment arms even in longer systems (Fig. 4).

Key findings II: Low-back loading and fatigue are strongly design dependent

The most pronounced differences between imaging systems were observed at the low back. In CT-guided simulations, low-back extensor torques were consistently higher when the additional mass of a typical protective lead apron was included (4.26 kg), despite the shorter reach distances. This finding aligns with established biomechanical evidence showing that external torso loads substantially increase spinal extensor demand [6]. At the low-back, about the lateral bend axis, endurance time was longest when performing a needle-insertion procedure in a CT scanner (Fig. 5). However, endurance time about the flexion/extension axis was lowest when simulating a needle-insertion task using the MAGNETOM Free.XL scanner, where endurance time was 46% lower (i.e. increased rate of fatigue) when simulating needle-insertion in CT relative to the MAGNETOM Free.XL.



5 Shoulder abduction/adduction and flexion/extension endurance times and low-back lateral bending and flexion/extension endurance times across three scanner models aggregated across avatar anthropometry and needle-insertion location. Higher values are interpreted as less fatiguing (i.e., the task could be performed for a longer time without fatiguing).

The MRI design featuring a flared bore, larger diameter, and elevated table height (MAGNETOM Free.XL) demonstrated markedly lower low-back flexion/extension torques and substantially longer endurance times compared with both conventional CT and a more conventional MRI geometry. These reductions were attributed to the combined effects of eliminating the lead apron load, improving access geometry, and reducing forward trunk flexion.

Discussion

Inclusivity and anthropometry

A critical contribution of this work is its explicit consideration of anthropometric diversity. Simulations showed that certain reach tasks were not feasible for the smallest avatar under specific MRI configurations unless table height or clinician elevation was adjusted. This finding highlights the importance of adjustable system features in supporting an inclusive interventional workforce.

Rather than treating reach limitations as individual shortcomings, the results emphasize the role of design in enabling safe and effective performance across a wide range of statures (Fig. 6).

Implications for scanner design and clinical practice

The findings synthesized here reinforce that ergonomic outcomes in interventional imaging are design dependent rather than modality dependent. Bore length, bore diameter, bore flaring, and table height interact to shape musculoskeletal loading and fatigue potential.

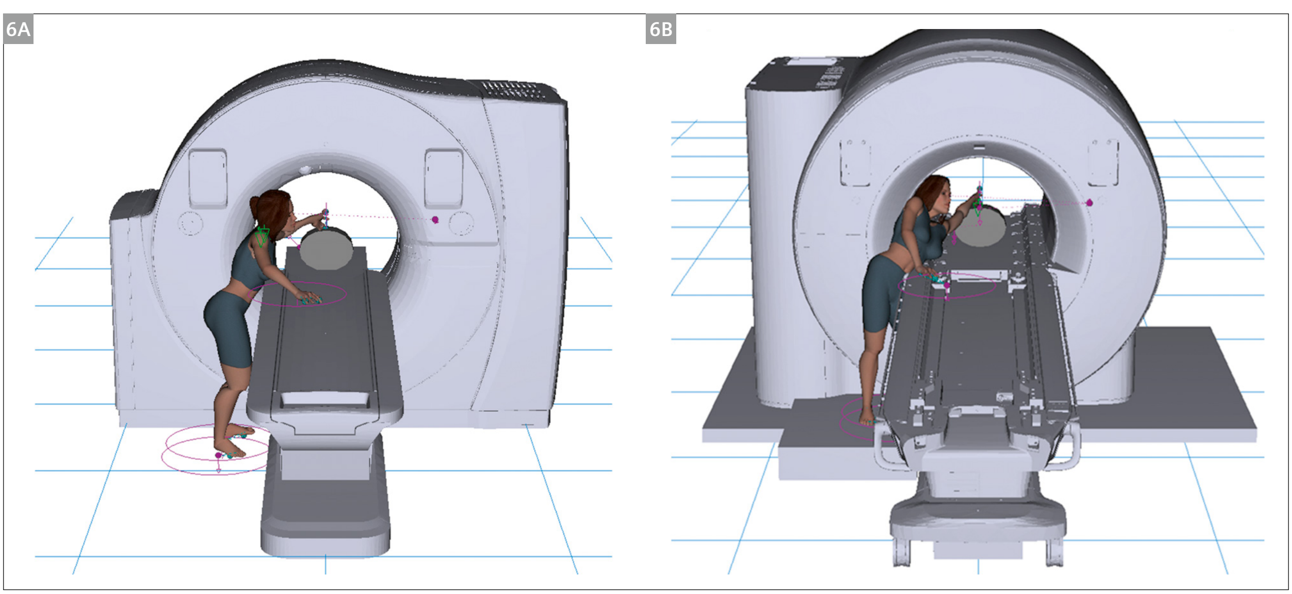
For manufacturers, DHM provides a powerful framework for evaluating ergonomic trade-offs early in the design process, complementing traditional performance metrics such as image quality and throughput [8]. For healthcare organizations, these insights support more informed procurement and service planning decisions, particularly as iMRI programs scale.

Future directions

Future work can extend DHM-based evaluation to longer procedures, dynamic task sequences, and team-based workflows. Advances in fatigue modeling and predictive simulation may further enhance realism and applicability [9]. Beyond hardware design, DHM may support training, workflow optimization, and procedure-specific setup recommendations based on clinician anthropometry.

Conclusion

Interventional MRI offers clear clinical advantages, but its long-term success depends on designing systems that support the people who use them. The work summarized here demonstrates that ergonomic risk in iMRI is neither inevitable nor uniform. Through validated digital human modeling, it is possible to identify design features that meaningfully reduce musculoskeletal loading, particularly at the low back, while maintaining clinical functionality. The 100 cm flared bore geometry of the MAGNETOM Free.XL appears to have ergonomic advantages compared with conventional CT and conventional 70 cm bore MRI geometries.



6 A lower scanner (left panel, **6A**) is more accessible for a woman in the 5th percentile for height. However, as illustrated in Figure 4, a lower scanner increases ergonomic risks for taller clinicians. However, the ability to match clinician hip height to the table height of the MAGNETOM Free.XL (right panel, **6B**), regardless of scanner height, offers an ideal solution.

By embedding ergonomics upstream in scanner design and service planning, the field can move beyond reactive mitigation and toward proactive prevention to support the sustainable, human-centered growth of interventional MRI.

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Further reading

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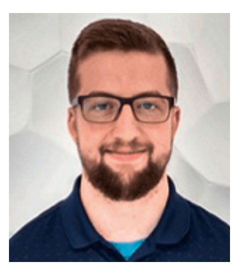

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