



Review

Computational lumbar spine models: A literature review

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ABSTRACT

Background: Computational spine models of various types have been employed to understand spine function, assess the risk that different activities pose to the spine, and evaluate techniques to prevent injury. The areas in which these models are applied has expanded greatly, potentially beyond the appropriate scope of each, given their capabilities. A comprehensive understanding of the components of these models provides insight into their current capabilities and limitations.

Methods: The objective of this review was to provide a critical assessment of the different characteristics of model elements employed across the spectrum of lumbar spine modeling and in newer combined methodologies to help better evaluate existing studies and delineate areas for future research and refinement.

Findings: A total of 155 studies met selection criteria and were included in this review. Most current studies use either highly detailed Finite Element models or simpler Musculoskeletal models driven with in vivo data. Many models feature significant geometric or loading simplifications that limit their realism and validity. Frequently, studies only create a single model and thus can't account for the impact of subject variability. The lack of model representation for certain subject cohorts leaves significant gaps in spine knowledge. Combining features from both types of modeling could result in more accurate and predictive models.

Interpretation: Development of integrated models combining elements from different model types in a framework that enables the evaluation of larger populations of subjects could address existing voids and enable more realistic representation of the biomechanics of the lumbar spine.

1. Introduction

Computational modeling has become a common and valuable tool in the study of the biomechanics of the spine. For more than 50 years, computational models have been employed to understand general spine function, assess the risk that different activities pose to the spine, evaluate different techniques and interventions to prevent injury, better understand the function of spines altered by disease or age, evaluate the impact of various surgical procedures, and even in the design and assessment of new surgical instrumentation. Over such a long course of development and research, modeling has become increasingly more complex and detailed and has expanded to a large range of different use cases. However, the majority of computational spine modeling has evolved to the point where it can be classified into just two primary categories. Musculoskeletal models have frequently been used for whole body, sports, and industrial biomechanics research, while finite element models are typically used in more detailed, clinically oriented research.

Both model types are very useful and have their own unique capabilities, but they both also have important limitations. In recent years, the use case for each model type has expanded greatly, potentially beyond the appropriate scope of each model given their capabilities. For example, static finite element models have been used to evaluate lifting and other dynamic work activities (Arjmand et al., 2012) while simplified rigid body musculoskeletal models have been used in the clinical space to evaluate surgical constructs (Benditz et al., 2018). The limitations inherent in each model type make their implementation in these specific use cases questionable. Furthermore, there are various other features of both model types whose limitations could have significant impacts on the results of these studies. In particular, the use of overly simplified models as well as very small numbers of subject-specific models is commonplace in the literature and likely results in study outcomes that are not representative of much of the population. Combining the best features from finite element and musculoskeletal modeling would most likely address many existing limitations, but relatively few models of

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this type exist. While a number of articles have reviewed and compared existing finite element (Dreischarf et al., 2014; Schmidt et al., 2012) and musculoskeletal models (Dreischarf et al., 2016; Rajaei et al., 2015) separately, to our knowledge, there have been no articles reviewing aspects of both together or combined modeling methodologies in the lumbar spine. Remus et al., 2021 provided a thorough introduction of these types of models and their use in other areas like the knee or in jaw-tongue-hyoid language simulations, but this is still relatively new in the field of spine research. Therefore, the objective of this review was to provide a critical assessment of the different characteristics of model elements employed across the spectrum of lumbar spine modeling and in newer combined methodologies to help better evaluate existing studies and delineate areas for future research and refinement.

2. Methods

2.1. Literature search

This review was based on an electronic literature search utilizing PubMed, Google Scholar, and Science Direct. The following keywords were used to gather relevant articles: lumbar, spine, model, biomechanical, finite element, and musculoskeletal. Literature review articles and the references for all included studies were also reviewed as a part of the search.

2.2. Study selection

The resulting articles were screened based on their title and abstract, and then the full text was evaluated to include in the review. Studies focused on the cervical or thoracic spine, models that did not include at least one full motion segment, cadaveric testing without associated computational modeling, sports biomechanics, scoliosis or spinal deformity, poroelastic modeling, spinal stability modeling, sudden loading, or animal modeling were excluded along with any non-English papers. Recognizing that more recent studies would feature increasingly advanced models able to take advantage of improved computational techniques and resources, the review was limited in scope to only articles published between 2011 and 2021. Only examining articles from the last ten years helped filter out less relevant models. However, older studies were frequently investigated to trace the evolution and composition of certain recent models.

2.3. Data extraction and evaluation

A series of different model characteristics were then recorded from each of the articles found. Articles were first subdivided into one of three categories based on Model Type: finite element modeling (FE), musculoskeletal modeling (MS), or Combined FE-MS modeling which employed elements of both FE and MS models. Next, they were categorized by Analysis Type into either static, dynamic, or quasi-static. The source of information used for the model geometry was also identified. This could include imaging data, literature databases, and various combinations of sources. Those studies that employed some kind of geometric simplification (enforced symmetry, level replication, etc.) were further described as simplified. Vertebrae representation described whether rigid or flexible elements were used to characterize each vertebral body. Similarly, IVD representation described the various elements used to represent the intervertebral discs. These included FE discs, spherical joints (3DoF), bushing-type elements (6DoF), and beam elements. A separate ligament representation was not included as these are not present across all model types. Ligaments are almost entirely absent from musculoskeletal models and are instead usually lumped in with the disc representations. Facet joint geometric representation described the sources of the facet surface geometry, simplifications employed, or if the geometric representation was only used for visualization. Muscle representation described the methodology employed to

represent loading from the lumbar musculature. And finally, the number of unique geometric models in each study are listed.

3. Results

3.1. Search results

The original search produced 9878 articles. After filtering out articles based on the selection parameters identified, a total of 155 articles were ultimately selected for this review. Fig. 1 describes the article search and selection process. Tables 1 and 2 describe articles with FE and MS models, respectively. Table 3 includes articles using Combined FE-MS models. Many articles utilized the same or nearly similar models with just minor differences in the experimental design or a different research focus. These articles were combined in each table where appropriate.

3.2. Model type

Finite element models were employed in 59 separate studies. Most of these studies relied on custom models usually created in commercial FE software packages. Musculoskeletal models were used in 82 studies. Many of these studies relied on the open-source software OpenSim (Simbios, California, USA) or the commercial software package Anybody (AnyBody Technology, Aalborg, Denmark). Fourteen studies utilized a Combined FE-MS model that employed FE and MS components in some fashion. These used a variety of open-source and commercial software packages along with custom models. Among the Combined FE-MS models, there were three different types of models. Uncoupled models (6 studies) used the results of one type of model as inputs for the other type. Coupled models (4 studies) iterate back and forth between the MS and FE models adjusting parameters to ensure spinal kinematics or other measures match within some error threshold. Integrated models combine elements from both MS and FE models in a single comprehensive computing environment instead of using parallel models. Only four studies used models with the Integrated methodology.

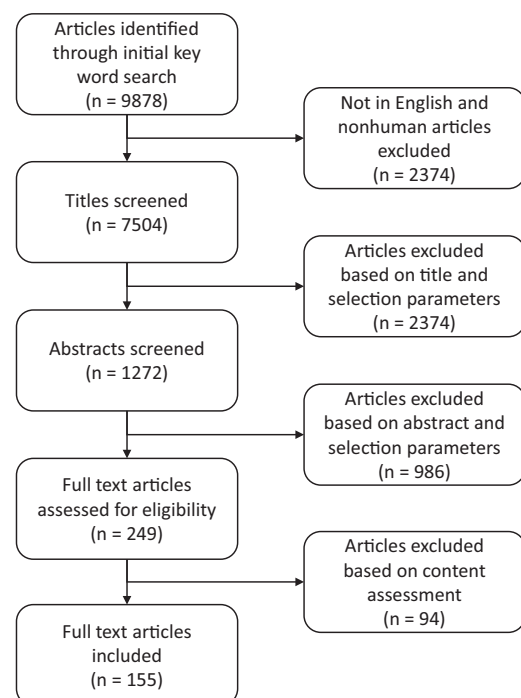


Fig. 1. Flow chart illustrating article search and selection process.

Table 1
Finite element (FE) model articles and associated model characteristics.

Reference	Analysis type	Model geometry	Vertebrae representation	IVD representation	Facet joint geometric representation	Muscle representation	Number of unique geometric models in each study
Ghezelbash et al., 2018, El Ouaaid et al., 2018, Shahvarpour et al., 2016, Ghezelbash et al., 2016a, Ghezelbash et al., 2016b, El Ouaaid et al., 2016, Ghezelbash et al., 2015, El Ouaaid et al., 2013a, El Ouaaid et al., 2013b, Arjmand et al., 2013, Arjmand et al., 2012	Static	CT-simplified	Rigid	Beam elements	–	Optimization	19,1,12,1,4,1,1,4,1,1,1
Bashkuev et al., 2020, Bashkuev et al., 2018, Niemeyer et al., 2012	Static	Parametric-simplified	FE	FE	Simplified geometry	Simulated in vitro testing	1000, 1000, 500
Campbell et al., 2016, Campbell and Petrella, 2015	Static	CT	FE	FE	CT	Simulated in vitro testing	18,18
Campbell and Petrella, 2016	Static	SSM	FE	FE	SSM	Simulated in vitro testing	35
Sohn et al., 2018, Choi et al., 2013	Static	CT-simplified	FE	FE	CT-simplified geometry	Simulated in vitro testing	1,1
Coombs et al., 2017	Static	CT	Rigid	FE	CT	Simulated in vitro testing	1
Dreischarf et al., 2015, Schmidt et al., 2012, Dreischarf et al., 2013, Dreischarf et al., 2012, Dreischarf et al., 2011	Static	CT-simplified	FE	FE	Literature-simplified geometry	Simulated in vitro testing	1,1,1,1,1
Galbusera et al., 2011	Static	CT-simplified	FE	FE	CT-simplified geometry	Simulated in vitro testing	1
Joukar et al., 2018	Static	CT	FE	FE	CT	Simulated in vitro testing	2
Seyed Vosoughi et al., 2019, Lindsey et al., 2018, Oktenoglu et al., 2015, Lindsey et al., 2015, Faizan et al., 2014, Erbulut et al., 2014, Agarwal et al., 2013, Kiapour et al., 2012a, Kiapour et al., 2012b	Static	CT-simplified	FE	FE	CT-simplified geometry	Simulated in vitro testing	1,1,1,1,1,1,1,1,1,1
Kim et al., 2015, Kim et al., 2013	Static	CT-simplified	FE	FE	CT-simplified geometry	Simulated in vitro testing	1,1
Little and Adam, 2015	Static	CT-simplified	FE	FE	CT-simplified geometry	–	3
Lo et al., 2019, Chen and Shih, 2018, Chen et al., 2015; Shih et al., 2012, Lin et al., 2013, Liu et al., 2011	Static	CT-simplified	FE	FE	CT-simplified geometry	Simulated in vitro testing	1,1,1,1,1,1
Meijer et al., 2011	Static	Parametric-simplified	Rigid	FE	Simplified geometry	Simulated in vitro testing	Numerous
Naserkhaki et al., 2018, Naserkhaki et al., 2016a, Naserkhaki et al., 2016b	Static	CT	FE	FE	CT	Simulated in vitro testing	1,3,1
Natarajan et al., 2018	Static	CT	FE	FE	CT	Simulated in vitro testing	1
Nikkhoo et al., 2020	Static	X-Ray-parametric-simplified	FE	FE	Simplified geometry	Simulated in vitro testing	10
Park et al., 2013	Static	CT-simplified	FE	FE	Literature-simplified geometry	Simulated in vitro testing	1
Sharabi et al., 2018	Static	CT	FE	FE	CT	Simulated in vitro testing	1
Song et al., 2014	Static	CT	FE	FE	CT	Simulated in vitro testing	1
Weisse et al., 2012	Static	CT	FE	FE	CT	Simulated in vitro testing	1
Ayturk and Puttlitz, 2011, Woldtvedt et al., 2011	Static	CT	FE	FE	CT	Simulated in vitro testing	1,1
Zander et al., 2017	Static	CT-simplified	FE	FE	Simplified geometry	Simulated in vitro testing	1
Zhang and Zhu, 2019	Static	CT	FE	FE	CT-simplified geometry	Simulated in vitro testing	1

3.3. Analysis type

Every FE model included in the review relied on a static analysis. The MS and Combined FE-MS models used a mix of static, quasi-static, or dynamic analyses. Oftentimes, the exact nature of the analysis was not clearly defined in the articles. Studies often featured dynamic input data,

but it was not always clear as to whether the simulation and analysis was truly dynamic, including the inertial impact of the body elements, or just quasi-static, performing a static analysis at each individual time point.

Table 2
Musculoskeletal (MS) model articles and associated model characteristics.

Reference	Analysis type	Model geometry	Vertebrae representation	IVD representation	Facet joint geometric representation	Muscle representation	Number of unique geometric models in each study
Abouhossein et al., 2013, Abouhossein et al., 2011	Dynamic	Literature-simplified	Rigid	6DoF	Literature-simplified geometry	Simulated in vitro testing	1,1
Actis et al., 2018	Dynamic	OpenSim Database	Rigid	6DoF	Visualization only	Optimization	15
Arshad et al., 2018, Arshad et al., 2017, Arshad et al., 2016, Zander et al., 2015, Han et al., 2013, Han et al., 2012	Static, Dynamic	Anybody Database	Rigid	3DoF, 6DoF	Visualization only	Optimization	6,1,1,4,1,1
Bassani et al., 2017	Dynamic	Anybody Database	Rigid	3DoF	Visualization only	Optimization	1
Bayoglu et al., 2019, Bayoglu et al., 2017	Quasi-static	CT-simplified	Rigid	3DoF	Visualization only	Optimization	1,1
Beaucage-Gauvreau et al., 2019	Dynamic	OpenSim	Rigid	3DoF	Visualization only	Optimization	3
Benditz et al., 2018, Putzer et al., 2016	Quasi-static/ Dynamic	Anybody Database/ Imaging	Rigid	3DoF	Visualization only/ Imaging	Optimization	31,5
Bruno et al., 2015	Static	OpenSim Database	Rigid	3DoF	Visualization only	Optimization	1
Cannon et al., 2021, Beach et al., 2019, Gooyers et al., 2018, McGill et al., 2014, Castanharo et al., 2014, McGill et al., 2013, Ikeda and McGill, 2012	Dynamic	Literature-simplified	Rigid	3DoF	Visualization only	EMG	18,20,32,14,21,9,4
Christophy et al., 2012	Dynamic	OpenSim Database	Rigid	6DoF	Visualization only	Optimization	1
Favier et al., 2021	Static	OpenSim/ MRI	Rigid	3DoF	Visualization only	Optimization	1
Guo et al., 2021	Dynamic	Literature-simplified	Rigid	6DoF	Simplified	Optimization	1
Huynh et al., 2015	Dynamic	Literature database	Rigid	3DoF	Visualization only	Optimization	1
Ignasiak et al., 2018, Ignasiak et al., 2016a, Ignasiak et al., 2016b	Dynamic	Anybody Database	Rigid	3DoF/6DoF	Visualization only	Optimization	1,1,1
Kim and Zhang, 2017	Dynamic	OpenSim Database	Rigid	6DoF	Visualization only	Optimization	13
Koopman et al., 2019, Kingma et al., 2016, Faber et al., 2011	Dynamic	Literature-simplified	Rigid	3DoF	–	EMG	10,10,9
Kuai et al., 2017	Dynamic	Anybody Database	Rigid	3DoF	Visualization only	–	33
Li and Chow, 2020a, Li and Chow, 2020b, Li and Chow, 2018	Dynamic	Literature-simplified	Rigid	3DoF	–	EMG/ Optimization	10,10,10
Malakoutian et al., 2016a, Malakoutian et al., 2016b	Dynamic	OpenSim Database	Rigid	6DoF	Visualization only	Optimization	1,1
	Dynamic	Anybody	Rigid	3DoF		Optimization	1

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Table 2 (continued)

Reference	Analysis type	Model geometry	Vertebrae representation	IVD representation	Facet joint geometric representation	Muscle representation	Number of unique geometric models in each study
Mirakhorlo et al., 2014					Visualization only		
Molinaro et al., 2020	Dynamic	OpenSim	Rigid	3DoF	Visualization only	EMG/Optimization	10
Mörl et al., 2020, Rupp et al., 2015	Quasi-static/Dynamic	Literature-simplified	Rigid	6DoF	Visualization only	Optimization	1,1
Nimbarte et al., 2013	Dynamic	Anybody Database	Rigid	3DoF	Visualization only	Optimization	10
Ning et al., 2012	Dynamic	MRI-simplified	Rigid	3DoF	–	EMG	11
Park et al., 2020, Park et al., 2012	Static	X-Ray-simplified	Rigid	3DoF	Visualization only	Optimization	1,3
Parkinson et al., 2011	Dynamic	MRI-simplified	Rigid	3DoF	–	EMG	12
Plamondon et al., 2017, Plamondon et al., 2014a, 2014b	Dynamic	Literature-simplified	Rigid	3DoF	–	–	45,30,45
Raabe and Chaudhari, 2018, Raabe and Chaudhari, 2016	Dynamic	OpenSim Database	Rigid	3DoF	Visualization only	Optimization	8,1
Samadi and Arjmand, 2018, Hajihosseinali et al., 2015, Mohammadi et al., 2015, Hajihosseinali et al., 2014	Static	CT-simplified	Rigid	3DoF	–	Optimization/EMG	1,1,1,1
Senteler et al., 2014	Dynamic	OpenSim Database/X-Ray	Rigid	6DoF	Visualization only	Optimization	81
Senteler et al., 2018, Senteler et al., 2017, Senteler et al., 2016	Static/Dynamic	OpenSim Database	Rigid	6DoF	Visualization only	Optimization	1,1,1
Wang et al., 2020	Quasi-static	OpenSim Database	Rigid	6DoF	Visualization only	Simulated In Vitro Testing	1
Zhu et al., 2021, Weston et al., 2020a, Weston et al., 2020b, Lavender et al., 2020, Picchiotti et al., 2019, Weston et al., 2018a, Weston et al., 2018b, Weston et al., 2017, Hwang et al., 2017, Hwang et al., 2016b, Le and Marras, 2016, Rose et al., 2013, Dufour et al., 2013, Splittstoesser et al., 2012, Le et al., 2012, Ferguson et al., 2012, Yang et al.,	Dynamic	MRI-simplified	Rigid	6DoF	Visualization only	EMG	12,30,10,14,10,62,12,62,12,12,20,16,10,20,10,10,12,12

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Table 2 (continued)

Reference	Analysis type	Model geometry	Vertebrae representation	IVD representation	Facet joint geometric representation	Muscle representation	Number of unique geometric models in each study
2011, Ferguson et al., 2011 Zwambag and Brown, 2020	Dynamic	Literature-simplified	Rigid	3DoF	–	Optimization	10

Table 3

Combined FE-MS model articles and associated model characteristics.

Reference	Analysis type	Model geometry	Vertebrae representation	IVD representation	Facet joint geometric representation	Muscle representation	Number of unique geometric models in each study
Dicko et al., 2015	Dynamic	Literature database	Rigid	FE	Literature-simplified geometry	Simulated in vitro testing	1
Gagnon et al., 2018, Gagnon et al., 2016, Gagnon et al., 2011	Dynamic	CT-simplified	FE	Beam elements/FE	Visualization only	EMG/Optimization	30,20,1
Honegger et al., 2021	Quasi-static	OpenSim database/CT	Rigid	3DoF/FE	CT	Optimization	8
Khoddam-Khorasani et al., 2020, Khoddam-Khorasani et al., 2018, Azari et al., 2018	Static	CT-simplified/CT	Rigid	Beam elements/FE	Visualization only/CT	Optimization	1,1,1
Knapik et al., 2012	Dynamic	CT/MRI OpenSim database/CT-simplified	Rigid	FE	CT	EMG	1
Kumaran et al., 2021	Static	Anybody database/CT-simplified	FE	FE	CT-simplified geometry	Optimization	1
Liu et al., 2019, Liu et al., 2018	Static	Anybody database	Rigid/FE	3DoF/FE	Simplified geometry	Optimization	1,1
Rajaei et al., 2021	Static	CT	Rigid	FE	CT	Optimization	1
Remus et al., 2021	Quasi-static	Visible Human Project – simplified	Rigid	FE	Literature-simplified geometry	Simulated in vitro testing	1

3.4. Model geometry

A wide variety of sources were used to create the spinal geometry of the models. CT imaging was the most frequently used source for the FE and Combined FE-MS models. In many cases the models featured significant simplifications to the CT-derived geometry that was either mentioned explicitly, referred to indirectly, or visually evident from included model graphics. These simplifications frequently included prescribed bilateral symmetry, reducing both image segmentation and model development efforts. Vertebrae replication was also included in some models. Here a single vertebral body model was replicated and then scaled, translated, and rotated to represent other spinal levels to reduce model development burden. In some cases, existing spine models were simply scaled to grossly match one or more dimensions of a new subject rather than creating a new subject-specific model. Surprisingly, most studies included little to no information detailing the construction process progressing from imaging data to a working model. The methods employed (tracing by hand, thresholding, region-growing, etc.) and specific segmentation parameters were usually absent. This obscures further simplifications that may have occurred in the modeling process and an assessment of the relative model characteristics. Existing literature geometric databases were used in both FE and MS models, but these were often for simplified geometric representations or parametric studies. Many of the MS studies relied on the spine geometry databases included in the Anybody or OpenSim software packages. Models generated from these databases were then often scaled to the test subjects with simple anthropometry measures or using imaging data. Overall, the MS models tended to have much simpler model geometry than the FE or Combined FE-MS models.

3.5. Vertebrae representation

Given the large stiffness of the vertebrae relative to the surrounding tissues, many of the MS and Combined FE-MS models, and even some FE models, represented the vertebrae as rigid bodies. This configuration reduces computational complexity and is often appropriate in non-clinical use cases. The remaining models treated the vertebrae as flexible bodies, usually including separate properties for the cancellous and cortical portions of the bone.

3.6. Intervertebral disc representation

The representation of the intervertebral discs was one of the greatest sources of variation between models. Three degree of freedom (3DoF) or spherical joints were the simplest representation and were frequently used in MS models as well as a few of the Uncoupled and Coupled Combined FE-MS models. These joints allow rotation about each axis, but no translation. Six degree of freedom (6DoF) joints or bushings are more complex, allowing rotation and translation. In some cases, these are represented by 6×6 stiffness matrices that include motion coupling. More frequently, only the diagonal terms in the matrices are included. Beam elements are more complex representations used in FE and Combined FE-MS models. These represent the overall nonlinear load-displacement response in each direction for each motion segment (including intervertebral disc, facets, and ligaments), often using results from previous detailed FE modeling. These offer an efficient method to represent the highly complex response of the motion segment, but do not allow for the investigation of the motion or loads in individual components. The most advanced disc representations used finite element modeling for each component of the disc (nucleus pulposus, annular

fibers, and vertebral endplates). There was considerable variety in the specific models and type of elements used for each component and in each study. Furthermore, the material properties used for each of the different types of disc representation varied from study to study. This was a function of both the literature source selected for the material properties and whether the IVD representation was an embodiment of all the components of the entire motion segment, just the intervertebral disc, or some combination of lumped and discrete elements.

3.7. Facet joint geometric representation

The facet joints are one of the most difficult elements to extract from imaging data, given the close proximity of adjacent vertebrae. As a result, they are frequently simplified in biomechanical models or omitted altogether. Nearly all MS models do not include any kind of facet joint representation other than just visualization. More than half of the FE and Combined FE-MS models feature simplified facet joint geometry. In many cases, the facets are simply represented as parallel planar surfaces with angles from the literature (Panjabi et al., 1993). In others, much of the vertebrae geometry is created from imaging data, while the facets are represented with a uniform gap between idealized articulating surfaces. Only 14 FE models and 6 Combined FE-MS models appear to feature facet surfaces extracted directly from imaging data, usually CT. Unfortunately, specific details about the exact methods of facet surface extraction were lacking from most studies and were often difficult to discern from model graphics. Thus, some of these models may in fact feature facets simplified in some respect.

3.8. Muscle representation

The lumbar musculature are responsible for the greatest proportion of loading on the lumbar spine. Nearly all of the FE models and 2 of the Combined FE-MS models did not include discrete musculature, but instead simulated in vitro testing, presumably because many studies referenced in vitro studies for validation or as a source of input data. This representation typically included a static moment in one of the cardinal planes along with a follower load applied along the curvature of the spine in order to stiffen the spine and account for the weight of the upper torso. The remaining Combined FE-MS models and nearly all the MS models included some type of distinct representation of the lumbar musculature. About half of these used electromyography (EMG) to derive muscle forces, while the other half used some type of optimization algorithm. The exact algorithms varied from study to study and in some cases hybrid algorithms were used that combined both types. Many studies collected EMG data, but then only used it to validate the muscle forces from optimization. These validations were usually qualitative in nature and often struggled to match the recorded EMG, especially the antagonistic muscles.

3.9. Number of unique geometric models in each study

The developmental and computational demands inherent in biomechanical modeling often restrict the number of models that can be created in each study. Many studies using MS models created large numbers of unique models given that these models were generally much simpler than their FE counterparts. In some cases, data was collected from a large number of subjects, but models were only created for a small subset or those at the extremes of a particular anthropometric measure. A number of studies specifically recruited subjects of a particular height and weight combination to match existing models, rather than make a new model for that subject. In 44 of the FE modeling studies and 11 of the Combined FE-MS, only a single model was created. Several FE studies created much larger numbers of models, but these were generally models that featured significant geometric simplifications. One set of studies created between 500 and 1000 unique models per study (Bashkuev et al., 2018; Bashkuev et al., 2020; Niemeyer et al.,

2012). These, however, were simple parametric models made from relatively basic shapes to conduct probabilistic studies examining the impact of spine geometry, material properties, and disc and facet degeneration on spinal loads. One study developed a large number of unique models using statistical shape modeling, though these were virtual rather than actual subjects (Campbell and Petrella, 2016). Reusing a specific model appears to be quite common, especially in FE models studies. It appears that in some cases, the same exact model was reused across a large number of studies over many years.

The small number of unique models created, and reuse of certain models across numerous publications restricts the amount of the population represented in these studies. Figs. 2–5 show histograms describing the demographic information for the models in this review that included full, detailed representations of the vertebrae. They show the break down in gender of the models created, the distribution in age of the subjects on which the models were based, and the distribution in subject heights and weights. Not all studies are represented in these histograms as many did not provide any subject demographic information. In some cases, one or more of the measures were not included. It is evident that certain portions of the population are underrepresented in these studies. Only 7 studies included models of females, though it is possible there are others since subject gender was not specified in many studies. While a large variety of ages is represented overall, certain ranges only included 1 or 2 subjects. Similarly, for height and weight, certain ranges are well represented, but then others only include a few subjects. There are almost no models of subjects at the extremes of heights and weights.

4. Discussion

Computational spine modeling must strike a balance between realism and practicality. This applies to data collection (number of subjects, number of trials, number and type of sensors, imaging requirements), model development (number of models, included elements, methods employed, simplifications), and model processing (number of models and trials, computational methods, parameters, simplifications). The purpose and specific goals of each study play a large part in dictating how a balance is achieved in each of these aspects. Clinically focused studies often featured highly detailed FE models of the spine with great computational complexity. This limits the number of models, the types of analyses, and often requires numerous simplifications. Industrial biomechanics studies typically use much lower fidelity MS models, but are able to include greater numbers of subjects, sensor inputs, and trials. Across the many studies reviewed, practicality was chosen for certain characteristics at the expense of realism. Assessing the strengths and weaknesses of each characteristic evaluated allows for identification of the most realistic elements and areas for future development.

FE models include flexible/deformable individual vertebrae, discs, facet joints, and ligaments each with their own material properties, often derived from cadaveric studies. This sophistication enables very detailed investigation into individual tissue deformations and stresses. And since there are various tissue tolerance limits in the literature, this enables an assessment of specific injury risk as well. This is also the best method to evaluate different surgical constructs as they can be modeled in detail and their performance and potential side-effects can be considered. However, this greater detail requires significantly greater computational effort which often places important limits on the types of analyses performed and the composition of these models. In addition, many concessions are made to simplify models to reduce computational burden and development costs. In the clinical space, these simplifications and the small number of unique models is noteworthy and calls into question how generalizable the results are for the entire potential patient population.

MS models typically treat bones as rigid bodies connected via simple kinematic or kinetic joints. This enables these models to include the impact of large whole-body motions and deformations, often using optical, magnetic, goniometric, or inertial motion capture inputs. They can

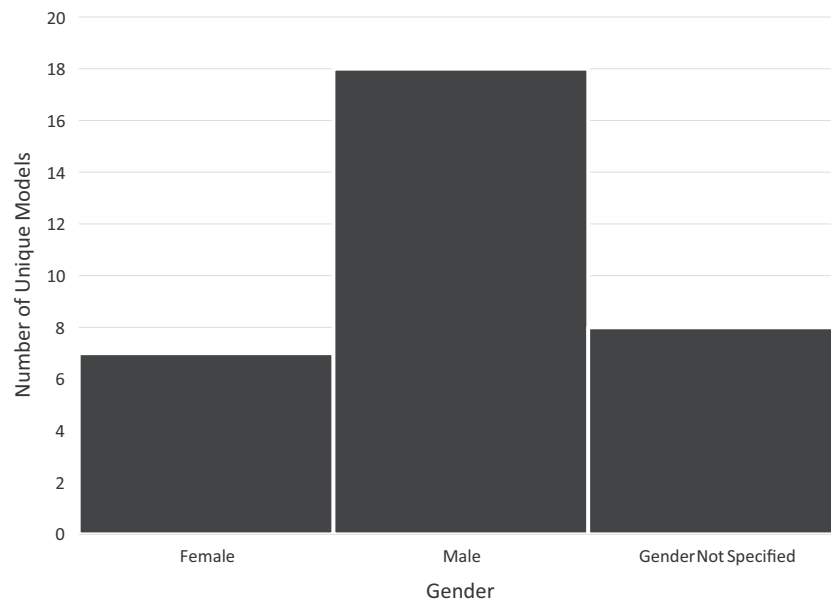


Fig. 2. Histogram describing the gender breakdown of computational models in this review.

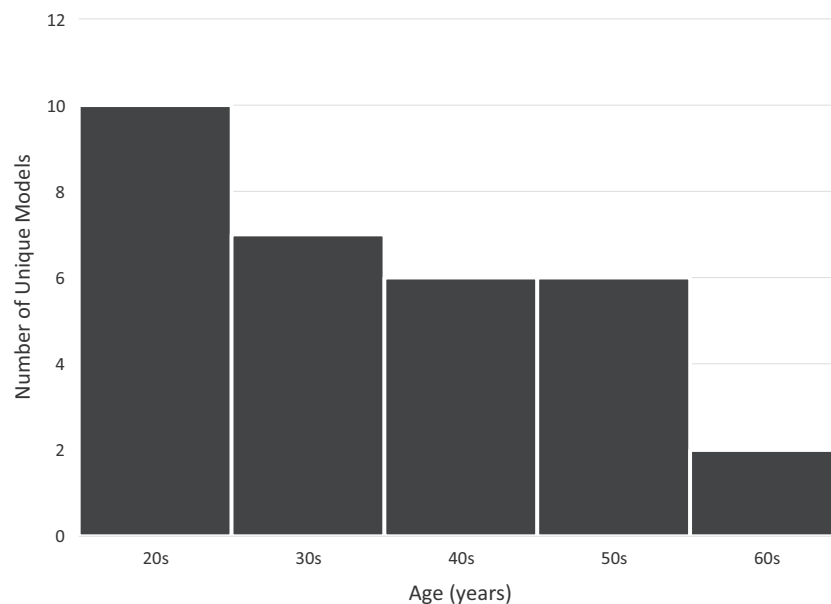


Fig. 3. Histogram describing the distribution of ages represented by computational models in this review.

also include various types of muscle and other soft tissue representations. Overall, MS models are simpler computationally, allowing for more complex analyses and model elements as well as a greater number of subjects and trials. They are not, however, generally appropriate for the same type of detailed analysis as FE models and usually report overall loads on motion segments and not on specific tissues.

Combined FE-MS models blend elements of MS and FE models by allowing advanced whole-body simulations while still focusing on detailed analyses of specific tissues. Uncoupled and Coupled models require a parallel set of models, one MS and one FE. Unfortunately, coordination of the two is often difficult given the distinct computational methods, included elements, and various model properties. In Uncoupled models, there is no feedback to the original model, so there is often a mismatch in spinal kinematics between the two models. There is feedback with Coupled models which results in a closer correspondence in results but requires frequent iteration back and forth between models

to adjust parameters. As a result, they have greater computational demands and model convergence is not guaranteed.

Among the different types of Combined FE-MS models, Integrated models appear to have the most desirable characteristics. Specifically, since they combine both types of modeling within a single comprehensive computing environment, they don't require separate parallel models that may not match or require numerous iterations for agreement. This enables them to better capture the complex interdependent relationship between the active musculature and the passive spine components (Remus et al., 2021). While Integrated models have the greatest potential capabilities, they are still subject to any limitations inherent with the mix of other modeling characteristics employed.

The representation of the vertebrae is closely related to the type of model employed. Given the lower detail typical in MS models, utilizing rigid vertebrae is a reasonable and computationally convenient approach. This is usually an acceptable assumption as the vertebrae are

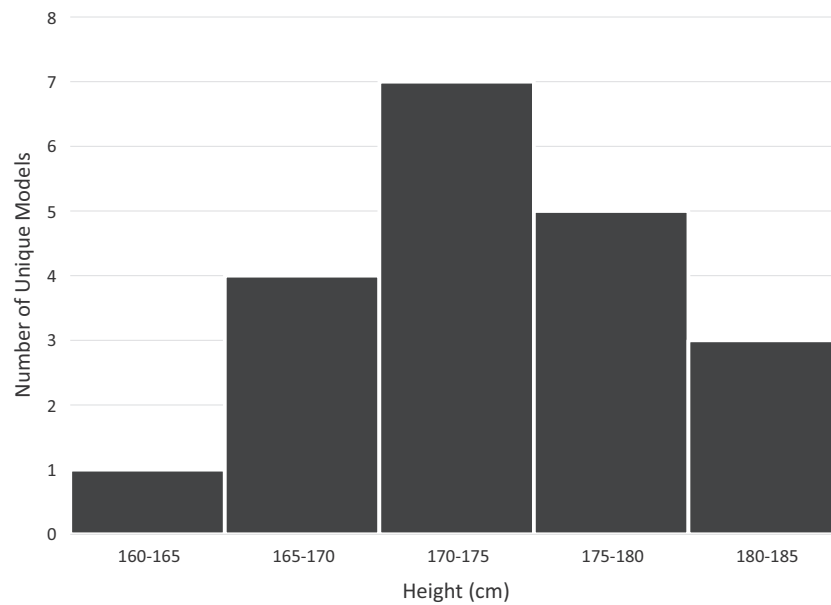


Fig. 4. Histogram describing the distribution of subject heights represented by the computational models in this review.

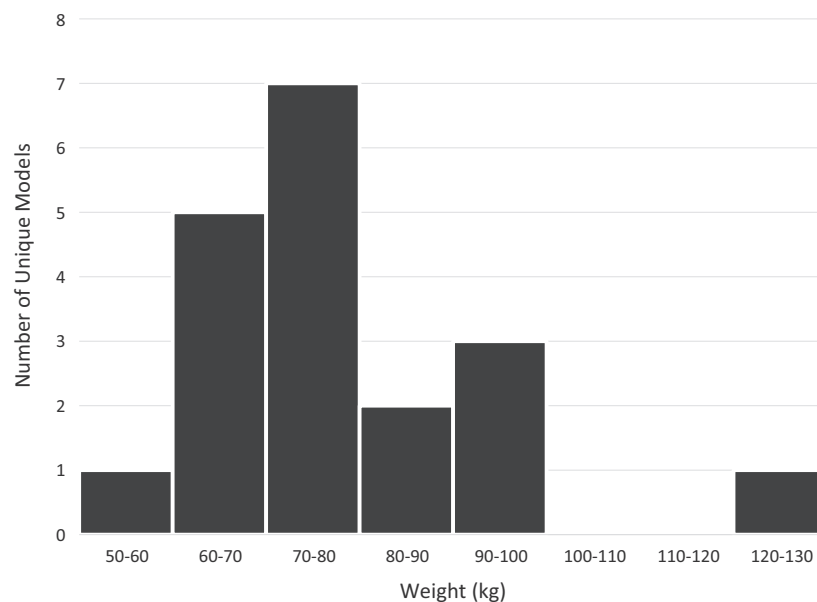


Fig. 5. Histogram describing the distribution of subject weights represented by the computational models in this review.

significantly stiffer than the surrounding soft tissue and thus do not deform a great deal unless under very large loads (Meijer et al., 2010). The greater detail typical in FE models often necessitates flexible vertebrae. This is especially true when evaluating various surgical procedures and constructs and their impact on the spine. The large stiffness of rods, screws, interbody devices, cement in vertebroplasty, and other typical surgical components means that the rigid vertebrae assumption is no longer valid. In addition, there is often interest in the bone/screw interface and possible pull-out, the potential for vertebral fractures, bone remodeling, and the performance of the surgical devices themselves. These all require flexible vertebrae. However, oftentimes the entire spine does not require flexible vertebrae and there is a benefit to being able to mix and match rigid and flexible depending on the spinal level. Thus, both representations have a place in spine modeling depending on a given study's goals, but the recent overlap in FE and MS model usage means that these are sometimes represented

inappropriately.

The representation of the intervertebral discs is also closely related to the type of model with all FE models employing detailed flexible discs or beam elements and MS models all using either 3 or 6 degree of freedom joints. Flexible discs are obviously much more realistic and permit the evaluation of loads on each of the various components of the disc. These models will usually also include detailed representations of the individual spinal ligaments. A variety of different element types and material properties have been used to represent the ligaments and have been reviewed elsewhere (Hamidrad et al., 2021; Naserkhaki et al., 2018). Since the disc is a frequent source of low back disorders, discrete modeling allows a detailed investigation into causal pathways and the progression of disc degeneration. None of the other disc representations permit this level of investigation and many are significantly less realistic. A number of Coupled and Uncoupled models reported significant mismatches between detailed and simpler disc models (Azari et al.,

2018; Khoddam-Khorasani et al., 2018; Khoddam-Khorasani et al., 2020; Liu et al., 2018; Liu et al., 2019). Several studies have also shown the importance of including disc translation for accurate modeling and thus indicate the limitations of 3DoF joints (Arshad et al., 2017; Dreischarf et al., 2016).

Regarding the type of analysis, basic physics confirms the importance of dynamics and motion and their impact on spinal loads. Unfortunately, neglecting the role of dynamics can result in a significant underestimation of loads on the spine. Since many activities of daily living and work tasks involve significant motion components, the large mass of the torso and any external loading can impart large dynamic forces on the spine. Previous studies have shown that neglecting dynamics can result in the underestimation of loads on the spine (Granata and Marras, 1995). Furthermore, dynamics and specifically spine kinematics has been shown to be both a predictor of workplace injuries (Marras et al., 1993a) and a key differentiator between the function of healthy and impaired spines (Marras et al., 1993b). Static modeling has been frequently used with FE models given their regular comparisons with in vitro studies that typically apply loads in a very slow manner. Unfortunately, this is an indictment on the realism and appropriateness of in vitro testing as a source of comparison and validation for FE models. Static and quasi-static modeling, while significantly simpler computational, are not representative of most in vivo loading and would most likely underestimate loads on the spine. Accordingly, dynamic analyses are important for realistic musculoskeletal modeling of the spine.

The shape and size of the vertebrae are known to vary widely throughout the population (Panjabi et al., 1992; Panjabi et al., 1993). There is also significant modeling evidence to suggest the unique geometry of the spine has a profound effect on spinal loading. Many simplified and parametric FE models have shown that manually manipulating different aspects of the spine's geometry such as disc area and height (Natarajan and Andersson, 1999), facet orientation (Kim et al., 2013; Robin et al., 1994), and vertebrae length, height, width, and other features (Bashkuev et al., 2018; Bashkuev et al., 2020; Lavaste et al., 1992; Meijer et al., 2010; Meijer et al., 2011; Niemeyer et al., 2012) can all influence loading and the overall response of the spine. Other FE models have shown the importance of including more realistic curved facet surfaces instead of the more commonly used planar representations (Holzapfel and Stadler, 2006). More recent models have begun to show the differences between generic models and subject-specific models derived from imaging data (O'Reilly and Whyne, 2008). Thus, including subject-specific geometry in spine modeling is very important, especially when it comes to model validation (Jones and Wilcox, 2008). Biomedical imaging, primarily CT, provides the best means of including this geometry. Unfortunately, while the importance of making subject-specific models from imaging has been demonstrated, the great difficulty in creating these models has led to the use of significant geometric simplifications or just the development of a single detailed base model that is then reused across numerous studies (Jones and Wilcox, 2008). The geometry of the facet joints is most frequently simplified and thus may be among the most problematic areas. These simplifications, while computationally beneficial, could reduce the realism of model results. This could be especially problematic in clinical modeling as the complex geometric arrangement of surgical constructs during spine fusion and other surgeries suggests an important interaction with patient spine geometry. Clinical FE models very often feature simplified geometry and generally only a single model is evaluated. Unfortunately, the ultimate impact of these geometric simplifications on spinal loads has not been quantified to this point. Models developed using literature data or the databases included within OpenSim and Anybody are much easier to implement, but much simpler. They allow the creation of numerous models for the entire test population, but they both feature generic spinal geometry and have been described as inappropriate for subject-specific biomechanical modeling (Christophy et al., 2012; Ghezalbash et al., 2020c).

The same arguments for the importance of including subject-specific geometry apply for the number of models evaluated in each study. The important geometric variability present in the population suggests that not only should detailed, subject-specific models be created, but that each individual model would be expected to produce unique results. Thus, it would be important to create and evaluate a variety of models to get a more complete understanding of the population level response. Unfortunately, the limited numbers of subject-specific models present in each study and even across studies generally makes it impossible to perform any kind of statistical analysis of the results, let alone an assessment of the biomechanical response across the population or the impact of subject variability. Ultimately, this severely limits the generalizability of outcomes and prevents a full sensitivity analysis of the given model. This is especially important given the known variation in spinal geometry with age, gender, and other factors. The lack of adequate representation for certain cohorts leaves significant gaps in spine biomechanical knowledge. Females, certain age groups, and subjects at the highest and lowest percentiles for height and weight are especially underrepresented. Clearly there is a need for a more thorough understanding of the range of spine biomechanical responses across populations of subjects. The simplified geometry of MS models enables the easier evaluation of a much larger number of unique models; however, this level of detail is insufficient to capture the true impact of subject-specific geometry. Though, lessons learned about the important role of subject-specific kinematics and muscle forces in MS models does demonstrate the importance of including as much personalized detail and representation in spine biomechanical modeling as possible (Marras et al., 2000). This point could be extended to include subject-specific geometry as well.

Muscle force representation is an important differentiator between models. Muscle force algorithms usually come from either optimization routines or physiologic measures. In optimization (also called inverse-dynamic or inverse-static) models, the force developed in each muscle is computed to balance internal and external moment demands via algorithms that seek to minimize muscle stress, optimize stability, or are subject to other objectives. Models using physiologic measures (also called forward dynamic or biologically-assisted models) derive muscle forces directly from sensors monitoring biological signals, primarily EMG.

Optimization models are more common since they are far simpler to implement, as they don't require the extra hardware and expertise necessary for EMG studies. They are also readily available to implement in both OpenSim and Anybody. They do, however, have many limitations. Principally, optimization models lack a physiologic basis and thus are unable to replicate muscle force activation patterns like those measured in vivo. As a result, they are unable to account for inter- and intra-individual variability in muscle recruitment (Dreischarf et al., 2016). To combat this, studies will often average together postural information from multiple subjects and then solve for a single muscle activation pattern to be representative of the entire test population (Ghezalbash et al., 2020b). The limitations of these methods are especially prevalent when attempting to predict abdominal and oblique antagonistic muscle activity. Optimization algorithms will often predict no activity for these muscles (Liu et al., 2018), so many studies will simply assume a constant level of activity across various exertions (Khoddam-Khorasani et al., 2020). Making assumptions for these muscle groups or neglecting their impact altogether is especially problematic, as they have large moment arms relative to the spine and are often very active in individuals with low back disorders that demonstrate coactivity or guarding after injury (Marras et al., 2001). In addition, optimization models will also frequently feature an extremely large number of individual muscle fascicles, each with their own unique computed force. While very detailed, there is a question as to how generalizable this model structure is for the general population. Furthermore, the large number of fascicles often requires assumptions about muscle area and maximum muscle tension as well as the absence of the various active,

passive, force-length, and force-velocity components normally present in a Hill-type muscle model (Bayoglu et al., 2019). Optimization models have also been shown to be overly sensitive to spine kinematics and posture (Arshad et al., 2016), the specific muscle force algorithms employed (Park et al., 2020), and the kinetic representation of the spinal motion segment (Arshad et al., 2017). Ultimately, these collective limitations result in calculated muscle forces that simply do not match in vivo data (Ghezelbash et al., 2018; Raabe and Chaudhari, 2016). Since comparisons with in vivo EMG data are often used for validation purposes, this means these models often lack proper validation or instead rely on a qualitative rather than quantitative assessment of derived muscle force validity.

Models employing EMG to determine muscle forces doesn't suffer from many of the limitations present in optimization methods. They are, however, much more difficult to collect and implement correctly. They require specialized hardware, specific anatomic knowledge, and stringent standard operating procedures in order to collect reasonable data. In addition, a number of specific muscle parameters are required to account for all the elements present in the muscle force equations. These are often derived through thorough subject-specific calibration and then are combined with time dependent postural and velocity information (Hwang et al., 2016a; Hwang et al., 2016b). Since surface electromyography is most often used, that limits the direct use to only the shallower muscles and thus the deeper muscles are either neglected or assumed to activate using surrogate signals (Cholewicki and McGill, 1996). Fortunately, the muscles with the greatest mechanical advantage are readily accessible via surface EMG and previous studies using intramuscular electrodes have shown that many of the deeper muscles play a smaller role (Marras et al., 1984). Channel limitations and crosstalk also mean that these types of models generally represent the trunk musculature with far fewer muscle force vectors unless specific assumption are made about force distribution. While simpler in terms of the numbers of muscle vectors compared to their optimization model counterparts, it does allow the models to be more generalizable and still very sensitive to individual subject differences (Marras et al., 2000). Thus, models employing physiologic measures are better able to represent in vivo muscle forces for individual subjects. However, direct model validation is still difficult with existing technology. Often, the moment contribution of EMG-derived muscle forces is compared to external moment demands on the body to validate muscle force calculations. While the muscles often contribute the greatest proportion of load to the spine, this is still not a direct validation of loading on the disc and other structures in the spine.

The time- and posture-dependent nature, dynamic response, and overall complexity of the lumbar musculature make it too difficult to include in most FE modeling. Instead, most FE models typically apply simple static moments with a follower load. These are intended to be representative of the overall loads that are typically present on the spine but are significantly less complex and of a lower magnitude than those experienced in normal daily life. Unfortunately, recent research has shown that this combination of simplified loading fails to accurately represent the complex muscle recruitment forces and varying shear and compressive loads experienced in vivo (Khoddam-Khorasani et al., 2018). While this type of load evaluation enables direct comparison with in vitro testing, the benefits of this type of validation are questionable. In addition to load profiles and motions that do not match the conditions in vivo, cadaveric testing does not include active musculature and is subject to the hydration state, bone quality, and degree of disc degeneration of the specimen (Ghezelbash et al., 2020a; Honegger et al., 2021; Khoddam-Khorasani et al., 2018). Furthermore, in vitro experiment data outputs often feature large standard deviations, and many different combinations of model input parameters can produce outputs that fall within these result ranges. In lieu of robust validation methods, undertaking multiple comparisons can help provide more convincing evidence of model accuracy (Jones and Wilcox, 2008). Unfortunately, once again these studies typically only create a single model preventing a

comprehensive analysis of responses. Thus, it is evident that including the spinal musculature directly is far preferable over simulated in vitro testing.

Assessing the various characteristics of all the models reviewed, it becomes apparent that existing models in the literature have significant limitations and that a combination that includes aspects typical of both FE and MS models would be the most beneficial moving forward. The flexibility of Integrated models seems to provide the best method to include these various aspects. Unfortunately, each of the Integrated models reviewed lack one or more of the preferred characteristics previously discussed. Thus, there is an opportunity to address this void. Ideally, a biomechanical spine model would include detailed subject-specific geometry from imaging data with minimal simplifications, EMG-assisted muscle force elements, whole-body kinematics enabling dynamic analyses, and could be generated and processed at a scale that would allow thorough investigation of a large number of subjects. Future model development toward this target could yield improved models to guide spine injury prevention, diagnosis, and treatment.

5. Conclusions

Computational modeling is a valuable tool in the study of the biomechanics of the spine. This literature review identified and evaluated the many different characteristics of the various models employed in different areas of study. Of particular note, many frequently used model elements that feature important limitations. Many other model elements were found to provide more realistic representations of the spine than others in common use. Most current studies use either highly detailed FE models or simpler MS models. FE models are able to evaluate individual tissue deformations and stresses and even the impact of surgical instrumentation. Unfortunately, their greater complexity limits the number of models and types of analyses performed and often requires significant simplifications. MS models are able to evaluate whole body motions and deformations and typically include muscles and other soft tissues. Their simpler nature enables larger numbers of subjects to be evaluated. However, they do not include the same level of spinal detail as FE models and are limited in the types of possible analyses. The complementary strengths and limitations of each type of modeling suggests that an approach that combines elements of both types would be preferable and would allow for more accurate and predictive models. Unfortunately, there are relatively few models that combine the most realistic elements of both types, and none that are able to effectively evaluate large numbers of individual subjects to understand the variation of responses in the population. Thus, a void exists in the current computational spine modeling literature. Development of Integrated models combining elements of FE and MS modeling in a structure that enables the evaluation of entire populations of subjects could address this void and enable more realistic and effective representation of the biomechanics of the spine.

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References

- Abouhossein, A., Weisse, B., Ferguson, S.J., 2011. A multibody modelling approach to determine load sharing between passive elements of the lumbar spine. *Comput. Methods Biomech. Biomed. Eng.* 14 (6), 527–537. Jun.

- Abouhossein, A., Weisse, B., Ferguson, S.J., 2013. Quantifying the centre of rotation pattern in a multi-body model of the lumbar spine. *Comput. Methods Biomech. Biomed. Eng.* 16 (12), 1362–1373.
- Actis, J.A., Honegger, J.D., Gates, D.H., Petrella, A.J., Nolasco, L.A., Silverman, A.K., 2018. Validation of lumbar spine loading from a musculoskeletal model including the lower limbs and lumbar spine. *J. Biomech.* 68, 107–114. Feb 8.
- Agarwal, A., Palepu, V., Agarwal, A.K., Goel, V.K., Yildirim, E.D., 2013. Biomechanical evaluation of an endplate-conformed polycaprolactone-hydroxyapatite intervertebral fusion graft and its comparison with a typical nonconformed cortical graft. *J. Biomech. Eng.* 135 (6), 61005–61009. Jun.
- Arjmand, N., Plamondon, A., Shirazi-Adl, A., Parnianpour, M., Larivière, C., 2012. Predictive equations for lumbar spine loads in load-dependent asymmetric one- and two-handed lifting activities. *Clin. Biomech.* 27 (6), 537–544. Jul.
- Arjmand, N., Ekrami, O., Shirazi-Adl, A., Plamondon, A., Parnianpour, M., 2013. Relative performances of artificial neural network and regression mapping tools in evaluation of spinal loads and muscle forces during static lifting. *J. Biomech.* 46 (8), 1454–1462. May 31.
- Arshad, R., Zander, T., Dreischarf, M., Schmidt, H., 2016. Influence of lumbar spine rhythms and intra-abdominal pressure on spinal loads and trunk muscle forces during upper body inclination. *Med. Eng. Phys.* 38 (4), 333–338. Apr.
- Arshad, R., Zander, T., Bashkuev, M., Schmidt, H., 2017. Influence of spinal disc translational stiffness on the lumbar spinal loads, ligament forces and trunk muscle forces during upper body inclination. *Med. Eng. Phys.* 46, 54–62. Aug.
- Arshad, R., Angelini, L., Zander, T., Di Puccio, F., El-Rich, M., Schmidt, H., 2018. Spinal loads and trunk muscles forces during level walking - a combined in vivo and in silico study on six subjects. *J. Biomech.* 70, 113–123. Mar 21.
- Ayturk, U.M., Puttlitz, C.M., 2011. Parametric convergence sensitivity and validation of a finite element model of the human lumbar spine. *Comput. Methods Biomech. Biomed. Eng.* 14 (8), 695–705. Aug.
- Azari, F., Arjmand, N., Shirazi-Adl, A., Rahimi-Moghaddam, T., 2018. A combined passive and active musculoskeletal model study to estimate L4-L5 load sharing. *J. Biomech.* 70, 157–165. Mar 21.
- Bashkuev, M., Reitmaier, S., Schmidt, H., 2018. Effect of disc degeneration on the mechanical behavior of the human lumbar spine: a probabilistic finite element study. *Spine J.* 18 (10), 1910–1920. Oct.
- Bashkuev, M., Reitmaier, S., Schmidt, H., 2020. Relationship between intervertebral disc and facet joint degeneration: a probabilistic finite element model study. *J. Biomech.* 102, 109518. Mar 26.
- Bassani, T., Stucovitz, E., Qian, Z., Briguglio, M., Galbusera, F., 2017. Validation of the AnyBody full body musculoskeletal model in computing lumbar spine loads at L4/L5 level. *J. Biomech.* 58, 89–96. Jun 14.
- Bayoglu, R., Geeraedts, L., Groenen, K.H.J., Verdonshot, N., Koopman, B., Homminga, J., 2017. Twente spine model: a complete and coherent dataset for musculo-skeletal modeling of the lumbar region of the human spine. *J. Biomech.* 53, 111–119. Feb 28.
- Bayoglu, R., Galibarov, P.E., Verdonshot, N., Koopman, B., Homminga, J., 2019. Twente spine model: a thorough investigation of the spinal loads in a complete and coherent musculoskeletal model of the human spine. *Med. Eng. Phys.* 68, 35–45. Jun.
- Beach, T.A.C., Frost, D.M., Zehr, J.D., Howarth, S.J., McGill, S.M., Callaghan, J.P., 2019. Spine loading during laboratory-simulated fireground operations - inter-individual variation and method of load quantification. *Ergonomics* 62 (11), 1426–1438. Nov.
- Beaucage-Gauvreau, E., Robertson, W.S.P., Brandon, S.C.E., Fraser, R., Freeman, B.J.C., Graham, R.B., Thewlis, D., Jones, C.F., 2019. Validation of an OpenSim full-body model with detailed lumbar spine for estimating lower lumbar spine loads during symmetric and asymmetric lifting tasks. *Comput. Methods Biomech. Biomed. Eng.* 22 (5), 451–464. Apr.
- Benditz, A., Auer, S., Spörrer, J.F., Wolkerstorfer, S., Grifka, J., Suess, F., Dendorfer, S., 2018. Regarding loads after spinal fusion, every level should be seen separately: a musculoskeletal analysis. *Eur. Spine J.* 27 (8), 1905–1910. Aug.
- Bruno, A.G., Bouxsein, M.L., Anderson, D.E., 2015. Development and validation of a musculoskeletal model of the fully articulated thoracolumbar spine and rib cage. *J. Biomech. Eng.* 137 (8). Aug. 081003.
- Campbell, J.Q., Petrella, A.J., 2015. An automated method for landmark identification and finite-element modeling of the lumbar spine. *IEEE Trans. Biomed. Eng.* 62 (11), 2709–2716. Nov.
- Campbell, J.Q., Petrella, A.J., 2016. Automated finite element modeling of the lumbar spine: using a statistical shape model to generate a virtual population of models. *J. Biomech.* 49 (13), 2593–2599. Sep 6.
- Campbell, J.Q., Coombs, D.J., Rao, M., Rullkoetter, P.J., Petrella, A.J., 2016. Automated finite element meshing of the lumbar spine: verification and validation with 18 specimen-specific models. *J. Biomech.* 49 (13), 2669–2676. Sep 6.
- Cannon, J., Cambridge, E.D.J., McGill, S.M., 2021. Increased core stability is associated with reduced knee valgus during single-leg landing tasks: investigating lumbar spine and hip joint rotational stiffness. *J. Biomech.* 116, 110240. Feb 12.
- Castanharo, R., Duarte, M., McGill, S., 2014. Corrective sitting strategies: an examination of muscle activity and spine loading. *J. Electromyogr. Kinesiol.* 24 (1), 114–119. Feb.
- Chen, C.S., Shih, S.L., 2018. Biomechanical analysis of a new lumbar interspinous device with optimized topology. *Med. Biol. Eng. Comput.* 56 (8), 1333–1341. Aug.
- Chen, C.S., Huang, C.H., Shih, S.L., 2015. Biomechanical evaluation of a new pedicle screw-based posterior dynamic stabilization device (awesome rod system)—a finite element analysis. *BMC Musculoskelet. Disord.* 16, 81. Apr 9.
- Choi, K.C., Ryu, K.S., Lee, S.H., Kim, Y.H., Lee, S.J., Park, C.K., 2013. Biomechanical comparison of anterior lumbar interbody fusion: stand-alone interbody cage versus interbody cage with pedicle screw fixation - a finite element analysis. *BMC Musculoskelet. Disord.* 14, 220. Jul 26.
- Cholewicki, J., McGill, S.M., 1996. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin. Biomech.* 11 (1), 1–15. Jan.
- Christophy, M., Faruk Senan, N.A., Lotz, J.C., O'Reilly, O.M., 2012. A musculoskeletal model for the lumbar spine. *Biomech. Model. Mechanobiol.* 11 (1–2), 19–34. Jan.
- Coombs, D.J., Rullkoetter, P.J., Laz, P.J., 2017. Efficient probabilistic finite element analysis of a lumbar motion segment. *J. Biomech.* 61, 65–74. Aug 16.
- Dicko, A., Tong-Yette, N., Gilles, B., Faure, F., Palombi, O., 2015. Construction and validation of a hybrid lumbar spine model for the fast evaluation of intradiscal pressure and mobility. *World Acad. Sci. Eng. Technol. Int. J. Med. Health Biomed. Bioeng. Pharm. Eng.* 9, 139–150.
- Dreischarf, M., Rohlmann, A., Bergmann, G., Zander, T., 2011. Optimised loads for the simulation of axial rotation in the lumbar spine. *J. Biomech.* 44 (12), 2323–2327. Aug 11.
- Dreischarf, M., Rohlmann, A., Bergmann, G., Zander, T., 2012. Optimised in vitro applicable loads for the simulation of lateral bending in the lumbar spine. *Med. Eng. Phys.* 34 (6), 777–780. Jul.
- Dreischarf, M., Rohlmann, A., Zhu, R., Schmidt, H., Zander, T., 2013. Is it possible to estimate the compressive force in the lumbar spine from intradiscal pressure measurements? A finite element evaluation. *Med. Eng. Phys.* 35 (9), 1385–1390. Sep.
- Dreischarf, M., Schmidt, H., Putzier, M., Zander, T., 2015. Biomechanics of the L5-S1 motion segment after total disc replacement - influence of intraoceanic distraction, implant positioning and preoperative disc height on the range of motion and loading of facet joints. *J. Biomech.* 48 (12), 3283–3291. Sep 18.
- Dreischarf, M., Shirazi-Adl, A., Arjmand, N., Rohlmann, A., Schmidt, H., 2016. Estimation of loads on human lumbar spine: a review of in vivo and computational model studies. *J. Biomech.* 49 (6), 833–845. Apr 11.
- Dreischarf, M., Zander, T., Shirazi-Adl, A., Puttlitz, C.M., Adam, C.J., Chen, C.S., Goel, V.K., Kiapour, A., Kim, Y.H., Labus, K.M., Little, J.P., Park, W.M., Wang, Y.H., Wilke, H.J., Rohlmann, A., Schmidt, H., 2014. Comparison of eight published static finite element models of the intact lumbar spine: predictive power of models improves when combined together. *J. Biomech.* 47 (8), 1757–1766.
- Dufour, J.S., Marras, W.S., Knapik, G.G., 2013. An EMG-assisted model calibration technique that does not require MVCs. *J. Electromyogr. Kinesiol.* 23 (3), 608–613. Jun.
- El Ouaaid, Z., Shirazi-Adl, A., Arjmand, N., Plamondon, A., 2013a. Coupled objective function to study the role of abdominal muscle forces in lifting using the kinematics-driven model. *Comput. Methods Biomech. Biomed. Eng.* 16 (1), 54–65.
- El Ouaaid, Z., Shirazi-Adl, A., Plamondon, A., Larivière, C., 2013b. Trunk strength, muscle activity and spinal loads in maximum isometric flexion and extension exertions: a combined in vivo-computational study. *J. Biomech.* 46 (13), 2228–2235. Sep 3.
- El Ouaaid, Z., Shirazi-Adl, A., Plamondon, A., 2016. Effects of variation in external pulling force magnitude, elevation, and orientation on trunk muscle forces, spinal loads and stability. *J. Biomech.* 49 (6), 946–952. Apr 11.
- El Ouaaid, Z., Shirazi-Adl, A., Plamondon, A., 2018. Trunk response and stability in standing under sagittal-symmetric pull-push forces at different orientations, elevations and magnitudes. *J. Biomech.* 70, 166–174. Mar 21.
- Erbulut, D.U., Kiapour, A., Oktenoglu, T., Ozer, A.F., Goel, V.K., 2014. A computational biomechanical investigation of posterior dynamic instrumentation: combination of dynamic rod and hinged (dynamic) screw. *J. Biomech. Eng.* 136 (5). May. 051007.
- Faber, G.S., Kingma, I., van Dieën, J.H., 2011. Effect of initial horizontal object position on peak L5/S1 moments in manual lifting is dependent on task type and familiarity with alternative lifting strategies. *Ergonomics* 54 (1), 72–81. Jan.
- Faizan, A., Kiapour, A., Kiapour, A.M., Goel, V.K., 2014. Biomechanical analysis of various footprints of transforaminal lumbar interbody fusion devices. *J. Spinal Disord. Tech.* 27 (4), E118–E127. Jun.
- Favier, C.D., Finnegan, M.E., Quest, R.A., Honeyfield, L., McGregor, A.H., Phillips, A.T.M., 2021. An open-source musculoskeletal model of the lumbar spine and lower limbs: a validation for movements of the lumbar spine. *Comput. Methods Biomech. Biomed. Eng.* 24 (12), 1310–1325. Sep.
- Ferguson, S.A., Marras, W.S., Gary Allread, W., Knapik, G.G., Vandlen, K.A., Splittstoesser, R.E., Yang, G., 2011. Musculoskeletal disorder risk as a function of vehicle rotation angle during assembly tasks. *Appl. Ergon.* 42 (5), 699–709. Jul.
- Ferguson, S.A., Marras, W.S., Allread, W.G., Knapik, G.G., Splittstoesser, R.E., 2012. Musculoskeletal disorder risk during automotive assembly: current vs. seated. *Appl. Ergon.* 43 (4), 671–678. Jul.
- Gagnon, D., Arjmand, N., Plamondon, A., Shirazi-Adl, A., Larivière, C., 2011. An improved multi-joint EMG-assisted optimization approach to estimate joint and muscle forces in a musculoskeletal model of the lumbar spine. *J. Biomech.* 44 (8), 1521–1529. May 17.
- Gagnon, D., Plamondon, A., Larivière, C., 2016. A biomechanical comparison between expert and novice manual materials handlers using a multi-joint EMG-assisted optimization musculoskeletal model of the lumbar spine. *J. Biomech.* 49 (13), 2938–2945. Sep 6.
- Gagnon, D., Plamondon, A., Larivière, C., 2018. A comparison of lumbar spine and muscle loading between male and female workers during box transfers. *J. Biomech.* 81, 76–85. Nov 16.
- Galbusera, F., Bellini, C.M., Anasetti, F., Ciavarrò, C., Lovi, A., Brayda-Bruno, M., 2011. Rigid and flexible spinal stabilization devices: a biomechanical comparison. *Med. Eng. Phys.* 33 (4), 490–496. May.
- Ghezalbash, F., Arjmand, N., Shirazi-Adl, A., 2015. Effect of intervertebral translational flexibilities on estimations of trunk muscle forces, kinematics, loads, and stability. *Comput. Methods Biomech. Biomed. Eng.* 18 (16), 1760–1767.
- Ghezalbash, F., Shirazi-Adl, A., Arjmand, N., El-Ouaaid, Z., Plamondon, A., 2016a. Subject-specific biomechanics of trunk: musculoskeletal scaling, internal loads and

- intradiscal pressure estimation. *Biomech. Model. Mechanobiol.* 15 (6), 1699–1712. Dec.
- Ghezelbash, F., Shirazi-Adl, A., Arjmand, N., El-Ouaaid, Z., Plamondon, A., Meakin, J.R., 2016b. Effects of sex, age, body height and body weight on spinal loads: sensitivity analyses in a subject-specific trunk musculoskeletal model. *J. Biomech.* 49 (14), 3492–3501. Oct 3.
- Ghezelbash, F., El Ouaaid, Z., Shirazi-Adl, A., Plamondon, A., Arjmand, N., 2018. Trunk musculoskeletal response in maximum voluntary exertions: a combined measurement-modeling investigation. *J. Biomech.* 70, 124–133. Mar 21.
- Ghezelbash, F., Schmidt, H., Shirazi-Adl, A., El-Rich, M., 2020a. Internal load-sharing in the human passive lumbar spine: review of in vitro and finite element model studies. *J. Biomech.* 102, 109441. Mar 26.
- Ghezelbash, F., Shirazi-Adl, A., El Ouaaid, Z., Plamondon, A., Arjmand, N., 2020b. Subject-specific regression equations to estimate lower spinal loads during symmetric and asymmetric static lifting. *J. Biomech.* 102, 109550. Mar 26.
- Ghezelbash, F., Shirazi-Adl, A., Plamondon, A., Arjmand, N., 2020c. Comparison of different lifting analysis tools in estimating lower spinal loads - evaluation of NIOSH criterion. *J. Biomech.* 112, 110024. Nov 9.
- Gooyer, C.E., Beach, T.A.C., Frost, D.M., Howarth, S.J., Callaghan, J.P., 2018. Identifying interactive effects of task demands in lifting on estimates of in vivo low back joint loads. *Appl. Ergon.* 67, 203–210. Feb.
- Granata, K.P., Marras, W.S., 1995. An EMG-assisted model of trunk loading during free-dynamic lifting. *J. Biomech.* 28 (11), 1309–1317. Nov.
- Guo, J., Guo, W., Ren, G., 2021. Embodiment of intra-abdominal pressure in a flexible multi-body model of the trunk and the spinal unloading effects during static lifting tasks. *Biomech. Model. Mechanobiol.* 20 (4), 1599–1626. Aug.
- Hajihosseinali, M., Arjmand, N., Shirazi-Adl, A., Farahmand, F., Ghiasi, M.S., 2014. A novel stability and kinematics-driven trunk biomechanical model to estimate muscle and spinal forces. *Med. Eng. Phys.* 36 (10), 1296–1304. Oct.
- Hajihosseinali, M., Arjmand, N., Shirazi-Adl, A., 2015. Effect of body weight on spinal loads in various activities: a personalized biomechanical modeling approach. *J. Biomech.* 48 (2), 276–282. Jan 21.
- Hamidrad, S., Abdollahi, M., Badali, V., Nikkhoo, M., Naserkhaki, S., 2021. Biomechanical modeling of spinal ligaments: finite element analysis of L4-L5 spinal segment. *Comput. Methods Biomech. Biomed. Eng.* 24 (16), 1807–1818. Dec.
- Han, K.S., Zander, T., Taylor, W.R., Rohlmann, A., 2012. An enhanced and validated generic thoraco-lumbar spine model for prediction of muscle forces. *Med. Eng. Phys.* 34 (6), 709–716. Jul.
- Han, K.S., Rohlmann, A., Zander, T., Taylor, W.R., 2013. Lumbar spinal loads vary with body height and weight. *Med. Eng. Phys.* 35 (7), 969–977. Jul.
- Holzzapfel, G.A., Stadler, M., 2006. Role of facet curvature for accurate vertebral facet load analysis. *Eur. Spine J.* 15 (6), 849–856. Jun.
- Honegger, J.D., Actis, J.A., Gates, D.H., Silverman, A.K., Munson, A.H., Petrella, A.J., 2021. Development of a multiscale model of the human lumbar spine for investigation of tissue loads in people with and without a transtibial amputation during sit-to-stand. *Biomech. Model. Mechanobiol.* 20 (1), 339–358. Feb.
- Huynh, K.T., Gibson, I., Jagdish, B.N., Lu, W.F., 2015. Development and validation of a discretised multi-body spine model in LifeMOD for biodynamic behaviour simulation. *Comput. Methods Biomech. Biomed. Eng.* 18 (2), 175–184.
- Hwang, J., Knapik, G.G., Dufour, J.S., Aurand, A., Best, T.M., Khan, S.N., Mendel, E., Marras, W.S., 2016a. A biologically-assisted curved muscle model of the lumbar spine: model structure. *Clin. Biomech.* 37, 53–59. Aug.
- Hwang, J., Knapik, G.G., Dufour, J.S., Best, T.M., Khan, S.N., Mendel, E., Marras, W.S., 2016b. A biologically-assisted curved muscle model of the lumbar spine: model validation. *Clin. Biomech.* 37, 153–159. Aug.
- Hwang, J., Knapik, G.G., Dufour, J.S., Best, T.M., Khan, S.N., Mendel, E., Marras, W.S., 2017. Validation of a personalized curved muscle model of the lumbar spine during complex dynamic exertions. *J. Electromyogr. Kinesiol.* 33, 1–9. Apr.
- Ignasiak, D., Dendorfer, S., Ferguson, S.J., 2016a. Thoracolumbar spine model with articulated ribcage for the prediction of dynamic spinal loading. *J. Biomech.* 49 (6), 959–966. Apr 11.
- Ignasiak, D., Ferguson, S.J., Arjmand, N., 2016b. A rigid thorax assumption affects model loading predictions at the upper but not lower lumbar levels. *J. Biomech.* 49 (13), 3074–3078. Sep 6.
- Ignasiak, D., Rüeger, A., Sperr, R., Ferguson, S.J., 2018. Thoracolumbar spine loading associated with kinematics of the young and the elderly during activities of daily living. *J. Biomech.* 70, 175–184. Mar 21.
- Ikeda, D.M., McGill, S.M., 2012. Can altering motions, postures, and loads provide immediate low back pain relief: a study of 4 cases investigating spine load, posture, and stability. *Spine (Phila Pa 1976)* 37 (23), E1469–E1475. Nov 1.
- Jones, A.C., Wilcox, R.K., 2008. Finite element analysis of the spine: towards a framework of verification, validation and sensitivity analysis. *Med. Eng. Phys.* 30 (10), 1287–1304. Dec.
- Joukar, A., Shah, A., Kiapour, A., Vosoughi, A.S., Duhon, B., Agarwal, A.K., Elgafy, H., Ebraheim, N., Goel, V.K., 2018. Sex specific sacroiliac joint biomechanics during standing upright: a finite element study. *Spine (Phila Pa 1976)* 43 (18), E1053–E1060. Sep 15.
- Khoddam-Khorasani, P., Arjmand, N., Shirazi-Adl, A., 2018. Trunk hybrid passive-active musculoskeletal modeling to determine the detailed T12-S1 response under in vivo loads. *Ann. Biomed. Eng.* 46 (11), 1830–1843. Nov.
- Khoddam-Khorasani, P., Arjmand, N., Shirazi-Adl, A., 2020. Effect of changes in the lumbar posture in lifting on trunk muscle and spinal loads: a combined in vivo, musculoskeletal, and finite element model study. *J. Biomech.* 104, 109728. May 7.
- Kiapour, A., Ambati, D., Hoy, R.W., Goel, V.K., 2012a. Effect of graded facetectomy on biomechanics of Dynesys dynamic stabilization system. *Spine (Phila Pa 1976)* 37 (10), E581–E589. May 1.
- Kiapour, A., Anderson, D.G., Spenciner, D.B., Ferrara, L., Goel, V.K., 2012b. Kinematic effects of a pedicle-lengthening osteotomy for the treatment of lumbar spinal stenosis. *J. Neurosurg. Spine* 17 (4), 314–320. Oct.
- Kim, H.J., Zhang, Y., 2017. Estimation of lumbar spinal loading and trunk muscle forces during asymmetric lifting tasks: application of whole-body musculoskeletal modelling in OpenSim. *Ergonomics* 60 (4), 563–576. Apr.
- Kim, H.J., Chun, H.J., Lee, H.M., Kang, K.T., Lee, C.K., Chang, B.S., Yeom, J.S., 2013. The biomechanical influence of the facet joint orientation and the facet tropism in the lumbar spine. *Spine J.* 13 (10), 1301–1308. Oct.
- Kim, H.J., Kang, K.T., Son, J., Lee, C.K., Chang, B.S., Yeom, J.S., 2015. The influence of facet joint orientation and tropism on the stress at the adjacent segment after lumbar fusion surgery: a biomechanical analysis. *Spine J.* 15 (8), 1841–1847. Aug 1.
- Kingma, I., Faber, G.S., van Dieën, J.H., 2016. Supporting the upper body with the hand on the thigh reduces back loading during lifting. *J. Biomech.* 49 (6), 881–889. Apr 11.
- Knapik, G.G., Mendel, E., Marras, W.S., 2012. Use of a personalized hybrid biomechanical model to assess change in lumbar spine function with a TDR compared to an intact spine. *Eur. Spine J.* 21 (Suppl. 5), S641–S652. Jun.
- Koopman, A.S., Toxiri, S., Power, V., Kingma, I., van Dieën, J.H., Ortiz, J., de Looze, M. P., 2019. The effect of control strategies for an active back-support exoskeleton on spine loading and kinematics during lifting. *J. Biomech.* 91, 14–22. Jun 25.
- Kuai, S., Zhou, W., Liao, Z., Ji, R., Guo, D., Zhang, R., Liu, W., 2017. Influences of lumbar disc herniation on the kinematics in multi-segmental spine, pelvis, and lower extremities during five activities of daily living. *BMC Musculoskelet. Disord.* 18 (1), 216. May 25.
- Kumaran, Y., Shah, A., Katragadda, A., Padgaonkar, A., Zavatsky, J., McGuire, R., Serhan, H., Elgafy, H., Goel, V.K., 2021. Iatrogenic muscle damage in transforaminal lumbar interbody fusion and adjacent segment degeneration: a comparative finite element analysis of open and minimally invasive surgeries. *Eur. Spine J.* 30 (9), 2622–2630. Sep.
- Lavaste, F., Skalli, W., Robin, S., Roy-Camille, R., Mazel, C., 1992. Three-dimensional geometrical and mechanical modelling of the lumbar spine. *J. Biomech.* 25 (10), 1153–1164. Oct.
- Lavender, S.A., Sommerich, C.M., Bigelow, S., Weston, E.B., Seagren, K., Pay, N.A., Sillars, D., Ramachandran, V., Sun, C., Xu, Y., Marras, W.S., 2020. A biomechanical evaluation of potential ergonomic solutions for use by firefighter and EMS providers when lifting heavy patients in their homes. *Appl. Ergon.* 82, 102910. Jan.
- Le, P., Marras, W.S., 2016. Evaluating the low back biomechanics of three different office workstations: seated, standing, and perching. *Appl. Ergon.* 56, 170–178. Sep.
- Le, P., Dufour, J., Monat, H., Rose, J., Huber, Z., Alder, E., Radin Umar, R.Z., Hennessey, B., Dutt, M., Marras, W.S., 2012. Association between spinal loads and the psychophysical determination of maximum acceptable force during pushing tasks. *Ergonomics* 55 (9), 1104–1114.
- Li, S.S.W., Chow, D.H.K., 2018. Effects of backpack load on critical changes of trunk muscle activation and lumbar spine loading during walking. *Ergonomics* 61 (4), 553–565. Apr.
- Li, S.S., Chow, D.H., 2020a. Modified electromyography-assisted optimization approach for predicting lumbar spine loading while walking with backpack loads. *Proc. Inst. Mech. Eng. H* 234 (5), 527–533. May.
- Li, S.S.W., Chow, D.H.K., 2020b. Comparison of predictions between an EMG-assisted approach and two optimization-driven approaches for lumbar spine loading during walking with backpack loads. *Hum. Factors* 62 (4), 565–577. Jun.
- Lin, H.M., Pan, Y.N., Liu, C.L., Huang, L.Y., Huang, C.H., Chen, C.S., 2013. Biomechanical comparison of the K-ROD and Dynesys dynamic spinal fixator systems - a finite element analysis. *Biomed. Mater. Eng.* 23 (6), 495–505.
- Lindsey, D.P., Kiapour, A., Yerby, S.A., Goel, V.K., 2015. Sacroiliac joint fusion minimally affects adjacent lumbar segment motion: a finite element study. *Int. J. Spine Surg.* 9, 64. Nov 13.
- Lindsey, D.P., Kiapour, A., Yerby, S.A., Goel, V.K., 2018. Sacroiliac joint stability: finite element analysis of implant number, orientation, and superior implant length. *World J. Orthop.* 9 (3), 14–23. Mar 18.
- Little, J.P., Adam, C.J., 2015. Geometric sensitivity of patient-specific finite element models of the spine to variability in user-selected anatomical landmarks. *Comput. Methods Biomech. Biomed. Eng.* 18 (6), 676–688.
- Liu, C.L., Zhong, Z.C., Hsu, H.W., Shih, S.L., Wang, S.T., Hung, C., Chen, C.S., 2011. Effect of the cord pretension of the Dynesys dynamic stabilisation system on the biomechanics of the lumbar spine: a finite element analysis. *Eur. Spine J.* 20 (11), 1850–1858. Nov.
- Liu, T., Khalaf, K., Naserkhaki, S., El-Rich, M., 2018. Load-sharing in the lumbosacral spine in neutral standing & flexed postures - a combined finite element and inverse static study. *J. Biomech.* 70, 43–50. Mar 21.
- Liu, T., Khalaf, K., Adeb, S., El-Rich, M., 2019. Numerical investigation of intra-abdominal pressure effects on spinal loads and load-sharing in forward flexion. *Front. Bioeng. Biotechnol.* 7, 428. Dec 17.
- Lo, H.J., Chen, C.S., Chen, H.M., Yang, S.W., 2019. Application of an interspinous process device after minimally invasive lumbar decompression could lead to stress redistribution at the pars interarticularis: a finite element analysis. *BMC Musculoskelet. Disord.* 20 (1), 213. May 15.
- Malakoutian, M., Street, J., Wilke, H.J., Stavness, I., Dvorak, M., Fels, S., Oxland, T., 2016a. Role of muscle damage on loading at the level adjacent to a lumbar spine fusion: a biomechanical analysis. *Eur. Spine J.* 25 (9), 2929–2937. Sep.
- Malakoutian, M., Street, J., Wilke, H.-J., Stavness, I., Fels, S., Oxland, T., 2016b. A musculoskeletal model of the lumbar spine using ArtiSynth—development and validation. *Comput. Methods Biomech. Biomed. Eng. Imag. Vis.* 6 (5), 483–490.

- Marras, W.S., King, A.I., Joynt, R.L., 1984. Measurement of loads on the lumbar spine under isometric and isokinetic conditions. *Spine (Phila Pa 1976)* 9 (2), 176–187. Mar.
- Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A., Ferguson, S.A., 1993a. The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine (Phila Pa 1976)* 18 (5), 617–628. Apr.
- Marras, W.S., Parnianpour, M., Ferguson, S.A., Kim, J.Y., Crowell, R.R., Simon, S.R., 1993b. Quantification and classification of low back disorders based on trunk motion. *Eur. J. Phys. Med. Vienna Phys. Med. Award* 3 (6), 218–235.
- Marras, W.S., Davis, K.G., Heaney, C.A., Maronitis, A.B., Allread, W.G., 2000. The influence of psychosocial stress, gender, and personality on mechanical loading of the lumbar spine. *Spine (Phila Pa 1976)* 25 (23), 3045–3054. Dec 1.
- Marras, W.S., Davis, K.G., Ferguson, S.A., Lucas, B.R., Gupta, P., 2001. Spine loading characteristics of patients with low back pain compared with asymptomatic individuals. *Spine (Phila Pa 1976)* 26 (23), 2566–2574. Dec 1.
- McGill, S.M., Marshall, L., Andersen, J., 2013. Low back loads while walking and carrying: comparing the load carried in one hand or in both hands. *Ergonomics* 56 (2), 293–302.
- McGill, S.M., Cannon, J., Andersen, J.T., 2014. Muscle activity and spine load during pulling exercises: influence of stable and labile contact surfaces and technique coaching. *J. Electromyogr. Kinesiol.* 24 (5), 652–665. Oct.
- Meijer, G.J., Homminga, J., Hekman, E.E., Veldhuizen, A.G., Verkerke, G.J., 2010. The effect of three-dimensional geometrical changes during adolescent growth on the biomechanics of a spinal motion segment. *J. Biomech.* 43 (8), 1590–1597. May 28.
- Meijer, G.J., Homminga, J., Veldhuizen, A.G., Verkerke, G.J., 2011. Influence of interpersonnel geometrical variation on spinal motion segment stiffness: implications for patient-specific modeling. *Spine (Phila Pa 1976)* 36 (14), E929–E935. Jun 15.
- Mirakhorlo, M., Azghani, M.R., Kahrizi, S., 2014. Validation of a musculoskeletal model of lifting and its application for biomechanical evaluation of lifting techniques. *J. Res. Health Sci.* 14 (1), 23–28. Winter.
- Mohammadi, Y., Arjmand, N., Shirazi-Adl, A., 2015. Comparison of trunk muscle forces, spinal loads and stability estimated by one stability- and three EMG-assisted optimization approaches. *Med. Eng. Phys.* 37 (8), 792–800. Aug.
- Molinaro, D.D., King, A.S., Young, A.J., 2020. Biomechanical analysis of common solid waste collection throwing techniques using OpenSim and an EMG-assisted solver. *J. Biomech.* 104, 109704. May 7.
- Mörl, F., Günther, M., Riede, J.M., Hammer, M., Schmitt, S., 2020. Loads distributed in vivo among vertebrae, muscles, spinal ligaments, and intervertebral discs in a passively flexed lumbar spine. *Biomech. Model. Mechanobiol.* 19 (6), 2015–2047. Dec.
- Naserkhaki, S., Jaremko, J.L., Adeeb, S., El-Rich, M., 2016a. On the load-sharing along the ligamentous lumbosacral spine in flexed and extended postures: finite element study. *J. Biomech.* 49 (6), 974–982. Apr 11.
- Naserkhaki, S., Jaremko, J.L., El-Rich, M., 2016b. Effects of inter-individual lumbar spine geometry variation on load-sharing: geometrically personalized finite element study. *J. Biomech.* 49 (13), 2909–2917. Sep 6.
- Naserkhaki, S., Arjmand, N., Shirazi-Adl, A., Farahmand, F., El-Rich, M., 2018. Effects of eight different ligament property datasets on biomechanics of a lumbar L4-L5 finite element model. *J. Biomech.* 70, 33–42. Mar 21.
- Natarajan, R.N., Andersson, G.B., 1999. The influence of lumbar disc height and cross-sectional area on the mechanical response of the disc to physiologic loading. *Spine (Phila Pa 1976)* 24 (18), 1873–1881. Sep 15.
- Natarajan, R.N., Watanabe, K., Hasegawa, K., 2018. Biomechanical analysis of a long-segment fusion in a lumbar spine—a finite element model study. *J. Biomech. Eng.* 140 (9). Sep 1.
- Niemeyer, F., Wilke, H.J., Schmidt, H., 2012. Geometry strongly influences the response of numerical models of the lumbar spine—a probabilistic finite element analysis. *J. Biomech.* 45 (8), 1414–1423. May 11.
- Nikkhoo, M., Khoz, Z., Cheng, C.H., Niu, C.C., El-Rich, M., Khalaf, K., 2020. Development of a novel geometrically-parametric patient-specific finite element model to investigate the effects of the lumbar lordosis angle on fusion surgery. *J. Biomech.* 102, 109722. Mar 26.
- Nimbarte, A.D., Sun, Y., Jaridi, M., Hsiao, H., 2013. Biomechanical loading of the shoulder complex and lumbosacral joints during dynamic cart pushing task. *Appl. Ergon.* 44 (5), 841–849. Sep.
- Ning, X., Jin, S., Mirka, G.A., 2012. Describing the active region boundary of EMG-assisted biomechanical models of the low back. *Clin. Biomech.* 27 (5), 422–427. Jun.
- Oktenoglu, T., Erbulut, D.U., Kiapour, A., Ozer, A.F., Lazoglu, I., Kaner, T., Sasani, M., Goel, V.K., 2015. Pedicle screw-based posterior dynamic stabilisation of the lumbar spine: in vitro cadaver investigation and a finite element study. *Comput. Methods Biomech. Biomed. Eng.* 18 (11), 1252–1261. Aug.
- O'Reilly, M.A., Whyne, C.M., 2008. Comparison of computed tomography based parametric and patient-specific finite element models of the healthy and metastatic spine using a mesh-morphing algorithm. *Spine (Phila Pa 1976)* 33 (17), 1876–1881. Aug 1.
- Panjabi, M.M., Goel, V., Oxland, T., Takata, K., Duranceau, J., Krag, M., Price, M., 1992. Human lumbar vertebrae. Quantitative three-dimensional anatomy. *Spine (Phila Pa 1976)* 17 (3), 299–306. Mar.
- Panjabi, M.M., Oxland, T., Takata, K., Goel, V., Duranceau, J., Krag, M., 1993. Articular facets of the human spine. Quantitative three-dimensional anatomy. *Spine (Phila Pa 1976)* 18 (10), 1298–1310. Aug.
- Park, W.M., Wang, S., Kim, Y.H., Wood, K.B., Sim, J.A., Li, G., 2012. Effect of the intra-abdominal pressure and the center of segmental body mass on the lumbar spine mechanics - a computational parametric study. *J. Biomech. Eng.* 134 (1). Jan. 011009.
- Park, W.M., Kim, K., Kim, Y.H., 2013. Effects of degenerated intervertebral discs on intersegmental rotations, intradiscal pressures, and facet joint forces of the whole lumbar spine. *Comput. Biol. Med.* 43 (9), 1234–1240. Sep.
- Park, W.M., Kim, Y.J., Wang, S.B., Kim, Y.H., Li, G.A., 2020. Investigation of lumbar spine biomechanics using global convergence optimization and constant loading path methods. *Math. Biosci. Eng.* 17 (4), 2970–2983. Mar 31.
- Parkinson, R.J., Bezaire, M., Callaghan, J.P., 2011. A comparison of low back kinetic estimates obtained through posture matching, rigid link modeling and an EMG-assisted model. *Appl. Ergon.* 42 (5), 644–651. Jul.
- Picchiotti, M.T., Weston, E.B., Knapik, G.G., Dufour, J.S., Marras, W.S., 2019. Impact of two postural assist exoskeletons on biomechanical loading of the lumbar spine. *Appl. Ergon.* 75, 1–7. Feb.
- Plamondon, A., Delisle, A., Bellefeuille, S., Denis, D., Gagnon, D., Larivière, C., IRSST MMH Research Group, 2014a. Lifting strategies of expert and novice workers during a repetitive palletizing task. *Appl. Ergon.* 45 (3), 471–481. May.
- Plamondon, A., Larivière, C., Denis, D., St-Vincent, M., Delisle, A., IRSST MMH Research Group, 2014b. Sex differences in lifting strategies during a repetitive palletizing task. *Appl. Ergon.* 45 (6), 1558–1569. Nov.
- Plamondon, A., Larivière, C., Denis, D., Mecheri, H., 2017. Nastasia I; IRSST MMH research group. Difference between male and female workers lifting the same relative load when palletizing boxes. *Appl. Ergon.* 60, 93–102. Apr.
- Putzer, M., Ehrlich, I., Rasmussen, J., Gebbeken, N., Dendorfer, S., 2016. Sensitivity of lumbar spine loading to anatomical parameters. *J. Biomech.* 49 (6), 953–958. Apr 11.
- Raabe, M.E., Chaudhari, A.M.W., 2016. An investigation of jogging biomechanics using the full-body lumbar spine model: model development and validation. *J. Biomech.* 49 (7), 1238–1243. May 3.
- Raabe, M.E., Chaudhari, A.M.W., 2018. Biomechanical consequences of running with deep core muscle weakness. *J. Biomech.* 67, 98–105. Jan 23.
- Rajaeae, M.A., Arjmand, N., Shirazi-Adl, A., 2021. A novel coupled musculoskeletal finite element model of the spine - critical evaluation of trunk models in some tasks. *J. Biomech.* 119, 110331. Apr 15.
- Rajaeae, M.A., Arjmand, N., Shirazi-Adl, A., Plamondon, A., Schmidt, H., 2015. Comparative evaluation of six quantitative lifting tools to estimate spine loads during static activities. *Appl. Ergon.* 48, 22–32.
- Remus, R., Lipphaus, A., Neumann, M., Bender, B., 2021. Calibration and validation of a novel hybrid model of the lumbosacral spine in ArtiSynth-the passive structures. *PLoS One* 16 (4). Apr 26. e0250456.
- Robin, S., Skalli, W., Lavaste, F., 1994. Influence of geometrical factors on the behavior of lumbar spine segments: a finite element analysis. *Eur. Spine J.* 3 (2), 84–90.
- Rose, J.D., Mendel, E., Marras, W.S., 2013. Carrying and spine loading. *Ergonomics* 56 (11), 1722–1732.
- Rupp, T.K., Ehlers, W., Karajan, N., Günther, M., Schmitt, S., 2015. A forward dynamics simulation of human lumbar spine flexion predicting the load sharing of intervertebral discs, ligaments, and muscles. *Biomech. Model. Mechanobiol.* 14 (5), 1081–1105. Oct.
- Samadi, S., Arjmand, N., 2018. A novel stability-based EMG-assisted optimization method for the spine. *Med. Eng. Phys.* S1350-4533 (18), 30091–30092. Jun 23.
- Schmidt, H., Galbusera, F., Rohlmann, A., Zander, T., Wilke, H.J., 2012. Effect of multilevel lumbar disc arthroplasty on spine kinematics and facet joint loads in flexion and extension: a finite element analysis. *Eur. Spine J.* 21 (Suppl 5), S663–S674. Jun.
- Senteler, M., Weisse, B., Snedeker, J.G., Rothenfluh, D.A., 2014. Pelvic incidence-lumbar lordosis mismatch results in increased segmental joint loads in the unfused and fused lumbar spine. *Eur. Spine J.* 23 (7), 1384–1393. Jul.
- Senteler, M., Weisse, B., Rothenfluh, D.A., Snedeker, J.G., 2016. Intervertebral reaction force prediction using an enhanced assembly of OpenSim models. *Comput. Methods Biomech. Biomed. Eng.* 19 (5), 538–548.
- Senteler, M., Weisse, B., Rothenfluh, D.A., Farshad, M.T., Snedeker, J.G., 2017. Fusion angle affects intervertebral adjacent spinal segment joint forces-model-based analysis of patient specific alignment. *J. Orthop. Res.* 35 (1), 131–139. Jan.
- Senteler, M., Aiyangar, A., Weisse, B., Farshad, M., Snedeker, J.G., 2018. Sensitivity of intervertebral joint forces to center of rotation location and trends along its migration path. *J. Biomech.* 70, 140–148. Mar 21.
- Seyed Vosoughi, A., Joukar, A., Kiapour, A., Parajuli, D., Agarwal, A.K., Goel, V.K., Zavatsky, J., 2019. Optimal satellite rod constructs to mitigate rod failure following pedicle subtraction osteotomy (PSO): a finite element study. *Spine J.* 19 (5), 931–941. May.
- Shahvarpour, A., Shirazi-Adl, A., Larivière, C., 2016. Active-passive biodynamics of the human trunk when seated on a wobble chair. *J. Biomech.* 49 (6), 939–945.
- Sharabi, M., Levi-Sasson, A., Wolfson, R., Wade, K.R., Galbusera, F., Benayahu, D., Wilke, H.J., Haj-Ali, R., 2018. The mechanical role of the radial fibers network within the annulus fibrosus of the lumbar intervertebral disc: a finite elements study. *J. Biomech. Eng.* 141 (2), 021006. Oct 22.
- Shih, S.L., Chen, C.S., Lin, H.M., Huang, L.Y., Liu, C.L., Huang, C.H., Cheng, C.K., 2012. Effect of spacer diameter of the Dynesys dynamic stabilization system on the biomechanics of the lumbar spine: a finite element analysis. *J. Spinal Disord. Tech.* 25 (5), E140–149.
- Sohn, S., Park, T.H., Chung, C.K., Kim, Y.J., Jang, J.W., Han, I.B., Lee, S.J., 2018. Biomechanical characterization of three iliac screw fixation techniques: a finite element study. *J. Clin. Neurosci.* 52, 109–114. Jun.
- Song, C., Li, X.F., Liu, Z.D., Zhong, G.B., 2014. Biomechanical assessment of a novel L4/5 level interspinous implant using three dimensional finite element analysis. *Eur. Rev. Med. Pharmacol. Sci.* 18 (1), 86–94.

- Splittstoesser, R.E., Marras, W.S., Best, T.M., 2012. Immune responses to low back pain risk factors. *Work* 41 (Suppl 1(0 1)), 6016–6023.
- Wang, W., Wang, D., De Groote, F., Scheys, L., Jonkers, I., 2020. Implementation of physiological functional spinal units in a rigid-body model of the thoracolumbar spine. *J. Biomech.* 98, 109437. Jan 2.
- Weisse, B., Aiyangar, A.K., Affolter, Ch., Gander, R., Terrasi, G.P., Ploeg, H., 2012. Determination of the translational and rotational stiffnesses of an L4-L5 functional spinal unit using a specimen-specific finite element model. *J. Mech. Behav. Biomed. Mater.* 13, 45–61. Sep.
- Weston, E.B., Khan, S.N., Marras, W.S., 2017. Wheelchair pushing and turning: lumbar spine and shoulder loads and recommended limits. *Ergonomics* 60 (12), 1754–1765. Dec.
- Weston, E.B., Alizadeh, M., Knapik, G.G., Wang, X., Marras, W.S., 2018a. Biomechanical evaluation of exoskeleton use on loading of the lumbar spine. *Appl. Ergon.* 68, 101–108. Apr.
- Weston, E.B., Aurand, A., Dufour, J.S., Knapik, G.G., Marras, W.S., 2018b. Biomechanically determined hand force limits protecting the low back during occupational pushing and pulling tasks. *Ergonomics* 61 (6), 853–865. Jun.
- Weston, E.B., Aurand, A.M., Dufour, J.S., Knapik, G.G., Marras, W.S., 2020a. One versus two-handed lifting and lowering: lumbar spine loads and recommended one-handed limits protecting the lower back. *Ergonomics* 63 (4), 505–521. Apr.
- Weston, E.B., Dufour, J.S., Lu, M.L., Marras, W.S., 2020b. Spinal loading and lift style in confined vertical space. *Appl. Ergon.* 84, 103021. Apr.
- Woldtvedt, D.J., Womack, W., Gadomski, B.C., Schuldt, D., Puttlitz, C.M., 2011. Finite element lumbar spine facet contact parameter predictions are affected by the cartilage thickness distribution and initial joint gap size. *J. Biomech. Eng.* 133 (6), Jun. 061009.
- Yang, G., Marras, W.S., Best, T.M., 2011. The biochemical response to biomechanical tissue loading on the low back during physical work exposure. *Clin. Biomech.* 26 (5), 431–437. Jun.
- Zander, T., Dreischarf, M., Schmidt, H., Bergmann, G., Rohlmann, A., 2015. Spinal loads as influenced by external loads: a combined in vivo and in silico investigation. *J. Biomech.* 48 (4), 578–584. Feb 26.
- Zander, T., Dreischarf, M., Timm, A.K., Baumann, W.W., Schmidt, H., 2017. Impact of material and morphological parameters on the mechanical response of the lumbar spine - a finite element sensitivity study. *J. Biomech.* 53, 185–190. Feb 28.
- Zhang, H., Zhu, W., 2019. The path to deliver the most realistic follower load for a lumbar spine in standing posture: a finite element study. *J. Biomech. Eng.* 141 (3), 031010. Jan 7.
- Zhu, Y., Weston, E.B., Mehta, R.K., Marras, W.S., 2021. Neural and biomechanical tradeoffs associated with human-exoskeleton interactions. *Appl. Ergon.* 96, 103494. Oct.
- Zwambag, D.P., Brown, S.H.M., 2020. Experimental validation of a novel spine model demonstrates the large contribution of passive muscle to the flexion relaxation phenomenon. *J. Biomech.* 102, 109431. Mar 26.