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Finite element analysis of the rotator cuff: A systematic review

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Abstract

Background: Finite element modeling serves as a promising tool for investigating underlying rotator cuff biomechanics and pathology. However, there are currently no concrete guidelines for reporting in finite element model studies. This has compromised the reliability, validity, and reproducibility of literature due to omission of pertinent items within publications. Recently a Finite Element Model Grading Procedure has been proposed as a reporting guideline for model developers. The aim of this study was to conduct a systematic review of rotator cuff focused finite element models and characterize the reporting quality of those articles.

Methods: A comprehensive literature search was performed in PubMed, Web of Science, and Embase to find relevant articles. Each article was graded and given a reporting quality ranking based on a score generated from the Finite Element Model Grading Procedure.

Findings: We found that only 5/22 articles had scores of 75% or higher and fell within the “exceptional” reporting quality range. Most of the articles (16/22) fell within the “good” reporting quality range with scores between 50% and 75%. However, 9/16 articles within the “good” reporting quality range had scores below 60%.

Interpretation: This study indicates that improved guidelines and standards for good reporting practices must be made in the field of finite element modeling. Furthermore, it supports the use of the Finite Element Model Grading Procedure as an objective method for evaluating the quality of finite element model reporting in the literature.

Keywords

Shoulder; Rotator cuff; Finite element modeling; Systematic review

1. Introduction

Shoulder pain is the third most prevalent musculoskeletal disorder (Whittle and Buchbinder, 2015) and has been theorized to be due to pathology of the underlying rotator cuff tendons.

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Declaration of competing interest

Dr. Looft serves on the Minneapolis VA Healthcare System’s non-profit: Center for Veterans Research and Education (CVRE) Board of Directors as a non-paid member. Neither CVRE nor the VA were involved in the study design, implementation, data analysis or writing of this publication. Neither Dr. Ludewig nor Mr. Redepenning have any financial or personal conflicts of interest to report.

Rotator cuff tears affect > 20% of the population with the prevalence of systematic and asymptomatic rotator cuff tears increasing as one ages (Sher et al., 1995; Yamaguchi et al., 2006; Yamamoto et al., 2010). There are numerous theories for the pathophysiology of the rotator cuff including: variations in scapular anatomy (Bigliani et al., 1991; Neer, 1972; Spiegl et al., 2016), changes in tendon vascularity (Rathbun and Macnab, 1970), aging (Neer, 1983), chronic tensile (Soslowsky et al., 2002) and compressive loading (Ludewig and Reynolds, 2009; Neer, 1983) just to name a few.

Applying finite element (FE) modeling to clinical applications has been growing in popularity over the past twenty years (Fig. 1). Specifically for the rotator cuff, FE modeling has been used to analyze supraspinatus tear mechanics (Celemin et al., 2014; Engelhardt et al., 2014, 2016; Quental et al., 2016; Sano et al., 2007, 2013; Thunes et al., 2015), suture repair techniques (Funakoshi et al., 2008; Mantovani et al., 2016), glenohumeral implant design (Büchler and Farron, 2004), and the treatment and diagnosis of glenohumeral instability (Drury et al., 2010; Ellis et al., 2010; Favre et al., 2012).

The limitations, risks, and costs of conventional in vivo and cada-veric testing methods along with recent advancements in medical imaging and computational methods have made patient specific FE modeling an appealing option. While technological advancements have improved our modeling techniques, there has yet to be a consensus on guidelines adopted for reporting FE models akin to other fields such as: CONSORT recommendations (Moher et al., 2001) for reporting clinical trials and the ARRIVE guidelines (Kilkenny et al., 2010) for animal testing. Recent steps taken by the FDA to implement reporting guidelines for computational modeling studies to ensure reporting quality for medical devices (FDA, 2016), demonstrate the need for similar guidelines for FE modeling studies.

Consensus reporting guidelines are necessary for mitigating the lack of FE model transparency which is imperative for the transition of biomedical and clinical research to actual clinical practice. A Finite Element Model Grading Procedure (FEMGP) has been proposed with “the purpose of disseminating biomechanical models, publishing, and *evaluating others’ simulation research*; for journal editors and reviewers *judging manuscript quality*; for agencies and grant reviewers” (Erdemir et al., 2012, Appendix A).

The FEMGP provides an objective method for evaluating and judging whether an FE model manuscript provides the reader with the necessary information to recreate the reported FE model (i.e. reporting quality). The FEMGP also establishes a framework for future reporting procedures. Therefore, the overall purpose of this systematic review was to implement the FEMGP (Appendix A) to objectively assess the reporting quality of currently published FE models of the rotator cuff.

2. Methods

2.1. Literature search strategies

A three-part search strategy was used to elicit studies meeting the inclusion/exclusion criteria below: (1) we searched electronic databases for published work, using a comprehensive search strategy for FE models; (2) reference lists of primary studies included

in the review were manually searched for relevant publications; (3) publications were screened following the inclusion/exclusion criterion to determine relevant studies.

2.2. Database search

A comprehensive, electronic search strategy was conducted in Web of Science, PubMed, and Embase between January 20th and March 3rd 2017, for rotator cuff focused FE studies. The following search strategy was used in PubMed: ((“Shoulder Joint”[Title/Abstract] OR “Rotator Cuff”[Title/Abstract] OR “Scapula”[Title/Abstract] OR “Shoulder Joint”[Mesh] OR “Rotator Cuff”[Mesh] OR “Scapula”[Mesh] OR “Supraspinatus”[Title/Abstract] OR “Infraspinatus”[Title/Abstract] OR “Teres Minor”[Title/Abstract] OR “Subscapularis”[Title/Abstract]) AND (“Finite Element”[Title/Abstract] OR “Finite Element Analysis”[Mesh])). An identical search was performed in Web of Science and Embase: (“Shoulder Joint” OR “Rotator Cuff” OR “Scapula” OR “Supraspinatus” OR “Infraspinatus” OR “Teres Minor” OR “Subscapularis”) AND (“Finite Element” OR “Finite Element Analysis”). No terms for health or health outcomes were included to ensure all applications of FE modeling were identified. Bibliographies of primary studies and review articles meeting the inclusion/exclusion criteria were searched manually to identify further eligible studies.

2.3. Inclusion/exclusion criteria

To meet the inclusion/exclusion criteria, articles must contain a FE model of the rotator cuff tendons and/or muscles as either primary or secondary structures. Additionally, studies examining glenohumeral kinematics or the stress propagation through the tendons or muscular structures were also considered. This included: (1) models designed to improve diagnosis, investigation, monitoring and management of disease (2) models to assess geometrical differences between patients, (3) models for designing patient specific implants. Studies were excluded if analyses of the rotator cuff muscles/tendons were not included in model simulations. Articles in press, dissertations, non-peer reviewed data, and conference proceedings were not included in the review.

2.4. Study selection

Two independent reviewers (DHR & JML) screened titles and abstracts implementing the predefined inclusion/exclusion criterion. All studies meeting the inclusion/exclusion criterion were subject to an additional full text review by each review author. The final decision for inclusion was determined from the consensus of the two review authors and discrepancies were resolved with the consultation of a third member (PML).

2.5. Data collection

The independent review authors retrieved and compiled the following data in Microsoft Excel (2016) from each included article: study type and region of interest. Region of interest was defined as the primary anatomical region of focus in the model structure and output. Study type was categorized as either clinical, implant, suture repair, crash, or tear. Clinical studies were defined as those aimed to predict patient outcomes. This excluded those studies focused specifically on tear propagation and mechanics, as those were described as tear.

2.6. Finite element model grading

All articles retrieved from the literature search were subject to the in-depth FEMGP following data extraction. The FEMGP consists of items considered important for FE model reporting (outlined below). The FEMGP determined the quality of the articles elicited from the literature search. A cumulative FEMGP score was determined for each individual article based on the included items. The articles were then given a reporting quality ranking based on their FEMGP score.

The FEMGP included 6 groups consisting of individual items:

- *Model Identification* (20 items),
- *Model Structure* (9 items),
- *Simulation Structure* (6 items),
- *Verification* (6 items),
- *Validation* (9 items),
- and *Availability* (5 items).

Additionally, three of the items in the group *Model Structure* consisted of separate subgroups with individual items:

- *Loading and Boundary Conditions* (4 items),
- *Subcomponents* (17 items),
- and *Interactions* (4 items).

Separate individual subgroup scores were given for each loading and boundary condition, subcomponent, and interaction reported in the study. For an in-depth explanation of the FEMGP, see (Erdemir et al., 2012).

The FEMGP was performed independently by the two reviewers. All the FEMGP items were marked as either reported or not reported for each article. After each article was graded using the FEMGP, an FEMGP score (*i.e.* the overall quality percent score) was calculated for each article using Eq. (1).

$$FEMGP\ Score = \frac{1}{11} \left(\sum_{i=1}^8 GP_i + \frac{1}{N_S} \sum_{i=1}^{N_S} SP_i + \frac{1}{N_{LB}} \sum_{i=1}^{N_{LB}} LBP_i + \frac{1}{N_I} \sum_{i=1}^{N_I} IP_i \right) \quad (1)$$

where:

- GP is the percentage of items satisfied for a single group and is summed for all eight groups.
- SP is the percentage of items satisfied for a single subcomponent and is averaged across the total number of subcomponents (N_S).

- LBP is the percentage of items satisfied for a single loading or boundary condition and is averaged across the total number of loading and boundary conditions (N_{LB}).
- IP is the percentage of items satisfied for a single interaction and is averaged across the total number of interactions (N_I).
- FEMGP score was calculated as an average of all the group and subgroup percentages

Articles were then ranked based on their FEMGP score. The articles were ranked as either “exceptional”, “good”, “fair”, or “poor”. The ranking cutoffs were determined by the authors *a priori* to determine which articles were of similar or different reporting quality based on the FEMGP score, characterized as follows:

- “exceptional” (75–100%),
- “good” (50–74.9%),
- “fair” (25–49.9%),
- and “poor” (0–24.9%).

2.7. Statistical analysis

Statistical analysis was carried out on FMEGP scores to compare those articles published prior to 2010 and those published after 2010. Two separate student *t*-tests were performed. One student *t*-test was conducted on the FEMGP scores of articles published before and after 2010. The second student *t*-test was implemented on the combined verification and validation score between those published before and after 2010 to determine if there was a statistical difference.

3. Results

3.1. Literature search

A total of 513 articles were identified by our search protocol in three literature databases. This included 182 results from PubMed, 166 from Web of Science, and 165 from Embase. The 513 articles gathered from all three databases were screened for duplicates and, following duplicate removal, 195 non-duplicate articles remained for abstract screening. The inclusion criterion was applied during abstract screening to determine articles eligible for full text screening. There were 156 articles removed during abstract screening for not including the rotator cuff tendons or musculature in their model, and 39 articles were found eligible for full text screening. Fifteen more articles were removed during full text screening for not comprising any component of the rotator cuff in the model simulation. Additionally, during data extraction, 2 articles were removed for not analyzing kinematic or stress propagation in the rotator cuff. Therefore, 22 studies were included in the final analysis (Fig. 2).

3.2. Study characteristics

A majority of the 22 studies gathered from the literature search performed either clinical analysis ($n = 8$) or investigated rotator cuff tear mechanics ($n = 8$). The remaining studies analyzed either crash mechanics ($n = 2$), suture repair techniques ($n = 2$), or implant performance ($n = 2$). All studies examining tear mechanics focused on the supraspinatus as the primary region of interest (Table 1).

3.3. Grading results

All articles collected from the literature search were given quality scores based on the FEMGP score. Only minor discrepancies in grading were present between the two review authors, primarily for items within the groups *Verification* and *Validation*. Formal discussion between the two review authors resolved score discrepancies after agreement on formal definitions of disputed items. The final grading was based on the final agreed upon score. Five articles achieved scores that met the requirements for “exceptional” quality. One article was categorized as having “fair” quality based on the FEMGP score. All remaining articles achieved a quality score of “good”. However, 9 of the 16 articles within the “good” quality range had a FEMGP Score below 60% (Fig. 3).

A secondary analysis was conducted to determine whether overall improvements in reporting practices had occurred using a student *t*-test to compare the mean FEMGP scores between studies published before and after 2010. The year 2010 was selected post hoc to correspond to our finding that many of the articles in the exceptional category were published after the year 2010. As such, we acknowledge this secondary analysis includes inherent bias toward a significant difference. However, we found FEMGP scores only slightly increased from pre-2010 (mean 62%, SD 9%, $N = 13$) to post-2010 (mean 67%, SD 11%, $N = 9$), which was not a significant difference ($p = .32$) (Fig. 4).

4. Discussion

The purpose of this study was to objectively assess the reporting quality of currently published rotator cuff focused FE models using the FEMGP (Erdemir et al., 2012). The FEMGP can be used to measure the overall reporting quality of the FE model, and help researchers and reviewers assess the reliability, validity, and reproducibility of FE models. We successfully conducted a systematic review of the literature and identified 22 articles that met our inclusion/exclusion criteria (Fig. 2). Our study identified many of the study’s FEMGP scores fell below 60% (Fig. 3). Additionally, only five of the articles reached the “exceptional” quality range. However, all but one of the articles falling in the “exceptional” category (FEMGP score: 75–100%) were published after the year 2010.

This suggests there are an increasing number of rotator cuff FE model researchers practicing the reporting guidelines outlined in the FEMGP. It should be emphasized the FEMGP is not meant to assess the usability of the FE models but instead the overall reporting quality of the publication. A study receiving an FEMGP score of 75% does not necessarily have a better FE model than one with a score of 55%. However, a higher FEMGP score would indicate

easier reproducibility of the model as the study contains more relevant model development information.

4.1. FE model reporting quality

Improved guidelines and standards for good reporting practices in rotator cuff FE modeling are necessary for translation to clinical practice. The FEMGP provides an objective checklist of important elements necessary for promoting FE model quality and measuring improvements in reporting practices. Our secondary analysis demonstrates an increased awareness of better reporting practices among rotator cuff focused FE researchers, however, continued reporting improvements are needed (Fig. 4).

Improvements in reporting practices can be identified across many journals including Clinical Biomechanics whose editors require: “*submissions involving such modeling must comply with those requirements (see (Viceconti et al., 2005)). Authors must confirm... their paper complies with the journal’s requirements...*” (Clinical Biomechanics, 2018). However, consensus reporting guidelines adopted for publishing FE models akin to other fields (FDA, 2016; Kilkenny et al., 2010; Moher et al., 2001) are lacking. This is unfortunate as FE modeling is an important tool for improving our understanding of rotator cuff pathophysiology as well as addressing many other clinical questions.

4.2. FE model verification and validation

The groups *Verification* and *Validation* are the most pertinent in FE model research, as they are central to consider before any clinical significance can be assigned to model outputs. We found that articles with higher scores within the groups *Verification* and *Validation* were also generally of higher overall quality, according to the FEMGP score. All articles falling in the “exceptional” category reported 50% or more of the items in both *Verification* and *Validation* FEMGP groups. Overall, of the 22 articles, only 10 models satisfied 50% or more of verification items and only 9 articles met over 50% of the required items for validation (Fig. 5).

The importance of concrete verification and validation procedures has been addressed numerous times (Anderson et al., 2007; Hicks et al., 2015; Jones and Wilcox, 2008; Lund et al., 2012). However, the awareness is not reflected with higher FEMGP scores for verification and validation when we compared articles before and after 2010 using a *t*-test ($p = .15$). Due to the importance of proper verification and validation procedures (Anderson et al., 2007; Hicks et al., 2015; Jones and Wilcox, 2008; Lund et al., 2012), we wanted to take a closer look at two important steps often overlooked: mesh convergence (included in 4/22) and sensitivity analysis (included in 4/22). According to the National Agency for Finite Element Methods and Standards (NAFEMS) mesh convergence “*refers to the smallness of the elements required in a model to ensure that the results of an analysis are not affected by changing the size of the mesh.*”

Mesh convergence is an essential component for model optimization (Henninger et al., 2010) that requires at least 3 convergence runs. An output variable at a specific location is then plotted against the mesh density until the output variable no longer changes due to the changes in mesh density. Mesh convergence ensures proper meshing which is directly

related to the solution quality. It is common practice to have a more refined mesh at the region of interest and a coarser mesh further away, but it is important to ensure this gradient of mesh density does not impact the solution.

Another critical element of biomechanical modeling is conducting a sensitivity analysis (Anderson et al., 2007; Jones and Wilcox, 2008). A sensitivity analysis is a method for determining the relative importance of a different range of assumed input variables on the model output (Saltelli, 2002). This is accomplished by selecting a single output variable to assess while systematically changing the range of one assumed input variable at a time (Becker et al., 2011). The input variables are changed through a range of known plausible values to determine what impact the choice of magnitude of the input variable has on the selected output. This step is especially important in modeling biological tissues such as the rotator cuff, as subject specific material properties of the rotator cuff are inherently variable (Carpenter et al., 2005; Halder et al., 2000; Itoi et al., 1995).

In addition to very few studies conducting mesh convergence and sensitivity analyses, only 3/22 studies completed the FEMGP items: “*validation procedure*” and “*validated output*”. These results are consistent with other systematic review findings where < 20% of FE papers report having full model validation (Burkhart et al., 2013). FE model validation studies of complex living tissues (i.e. rotator cuff) are difficult and expensive due to the comparison data being either problematic or nearly impossible to directly measure/observe.

Two studies with experimental validation data were concerned with rotator cuff muscle moment arms (Adams et al., 2007; Webb et al., 2014), and both studies were able to directly validate the outputs of their respective models by comparing them with empirical data collected from human subjects. Another study that included validated model outputs was focused on rotator cuff tear mechanics (Thunes et al., 2015). The model was able to be validated against experimental data by comparing the stress-strain response from a supraspinatus tendon specimen.

While recommendations for conducting validation, procedures are available (Böl et al., 2011; Burkhart et al., 2013; Henninger et al., 2010), we found this process is either partially implemented or totally exempt from most rotator cuff focused FE models. Conversely, both mesh convergence and sensitivity analysis can be performed regardless of complex validation procedures. Though mesh convergence and sensitivity analysis are not equivalent to experimental validation, both contribute greatly in determining FE model quality.

It is often difficult to include much of the pertinent information for verification and validation in the report due to word limits in many journals. However, encouraging either separate reports for model development (Büchler et al., 2002b; Gatti et al., 2010; Moore et al., 2010) or additional information made available in a supplemental section (Favre et al., 2012; Mantovani et al., 2016; Quental et al., 2016) could help ensure the inclusion of items necessary for assessing model reliability and reproducibility. Alternatively, it has been suggested researchers make their models readily available (Rougier et al., 2017), along with pertinent information necessary to reproduce the simulation. Either way, researchers should present model information in the most accessible format (Pop and Salzberg, 2015).

4.3. FE model reliability and validity

Reliability and validity are considered the core of scientific proof. Reliability is concerned with the consistency of the model performance and outputs, while validity refers to the accuracy of the output or the agreement with *in vivo* measurements. Determining the reliability and validity of model outputs is important when evaluating simulation research and considering model results for research or clinical translation. For evaluation of model reliability and validity, *Model Structure*, *Verification*, and *Validation* groups are the most critical to consider in the overall quality score.

Model Structure is central for assessing reliability and validity since it contains items that determine the input-output relationship of the model (Erdemir et al., 2012). Inclusion of this information in a published manuscript allows the evaluator to determine the suitability of the data and relationships used for model development such as correctness of interactions and constitutive relationships. Among shoulder FE model studies, this information has been commonly placed within an independent model development section of the report (Adams et al., 2007; Duprey et al., 2007; Moore et al., 2010; Qental et al., 2016). Furthermore, supplementary tables providing characterizations for each structure within the model, as in Hwang et al. (2014), should be encouraged to enhance the overall readability of the report for reviewers.

Simply including all items within *Model Structure* won't provide enough information to determine overall reliability and validity of a rotator cuff model. *Verification* and *Validation* information must be included to prove the appropriateness of the data and formulations used for model development. Within *Verification*, items such as *Correctness of Formulation* and *Mesh Convergence* will support the use of the constitutive formulations and mesh density chosen within the study (Erdemir et al., 2012), respectively. Furthermore, items within *Validation* that provide the source and justification for the data and parameters in the model support the validity of the items reported in the *Model Structure*. Methods of material property extraction should also be included, as they were found to vary among articles included within this review.

4.4. FE model reproducibility

Reproducibility is one of the main pillars of scientific research. Reproducibility, within the perspective of computational modeling, is defined as the availability of all simulation inputs and relationships to repeat the simulation within a context different than presented in the original study. Problems with reproducibility are apparent within all areas of scientific research (Munafò et al., 2017; Rougier et al., 2017), including FE modeling.

Guidelines to ensure complete transparency of methods should be followed to ensure model reproducibility is attainable within the scientific community. The FEMGP could be used as both a guideline for reproducibility and a self-assessment tool, to gage the completeness of reporting methods prior to publication. Reviewers could use the FEMGP to determine whether a model meets the publication requirements for reproducibility. The key categories to evaluate for emphasis on reproducibility are *Simulation Structure*, *Model Structure*, *Verification*, and *Validation*. *Simulation Structure* and *Model Structure* both contain the

necessary information to reconstruct the model with identical features and conditions to those used in the study (Erdemir et al., 2012).

Since each FE simulation platform or software version may possess different competences (Maas et al., 2012), the items within *Simulation Structure* are of considerable importance. Use of an alternative FE solving platform may produce inconsistent results when attempting to reproduce a study. Furthermore, if default settings were not used within simulation software, those should be noted in addition to the name and version of the FE solver used.

Reporting should also cover the items in *Model Structure* to permit complete reconstruction of all components and interactions in the model. Some rotator cuff studies have even included separate sections describing interactions along with loading and boundary conditions within the model (Debski et al., 2005; Hwang et al., 2014; Sano et al., 2013). In addition to allowing reconstruction of the original model, providing these items warrants users to modify or add to the model to meet individual research requirements.

Verification and *Validation* items, along with proving the reliability and validity of the model, provide information on the limits of the predictive capacity of the model when supplied with different inputs (*Sensitivity Analysis* and *Predictive Capacity*) or when run on different platforms (*Assessment of Repeatability*). Therefore, this information is necessary to ensure repeatability and function of the model when implemented in a separate research study.

The location of the reported verification and validation items were found to vary within this study (Quental et al., 2016; Thunes et al., 2015; Webb et al., 2014). Furthermore, they were not distinctly labeled, making it difficult for reviewers to locate these items within the report. Therefore, more in-depth recommendations for how to report these items should be established to allow readers to more easily assess the reliability, validity, and reproducibility of rotator cuff models. While all items within the FEMGP are neither exhaustive nor completely essential for reliability, validity, and reproducibility, they should be considered when reporting in a FE study. Reporting should at least cover the minimum information necessary to reproduce the study and ensure reliability and validity of results.

4.5. Study limitations

This study has three primary limitations. First, only three literature databases were included in the comprehensive literature search. Therefore, articles relevant to this study present in other literature databases could have been missed. However, all relevant databases, to the authors' knowledge, were included in the literature search. Our search criteria did neglect the whole human body or torso models that could have potentially included the rotator cuff and surrounding structures. Thus, it is possible a few articles pertinent to this study were missed.

Second, the data analysis in this study was only performed by two review authors. Though the FEMGP is primarily an objective method of determining model quality, subjective opinions by each reviewer could affect overall grading results. Items can also be prone to individual interpretation. In this study, there were no significant disagreements between the

two reviewers. However, minor discrepancies between grading results were occasionally present and were resolved after conversation between the two review authors. Finally, due to the limited number of reviewers, items within certain articles could have been overlooked during the grading process. FEMGP scores should therefore be considered within a quality range rather than as an exact score.

4.6. FEMGP usability

Burkhart et al. (2013) were the first group to assess and quantify specific areas included within the FEMGP. However, they did not assess overall reporting quality. This study expands upon Erdemir et al. (2012) and Burkhart et al. (2013) to expand the FEMGP to include a grading component that can help assess and categorize the overall reporting quality of FE model publications. One item to note is the amount of time required to use the FEMGP. Depending on how the information is presented in the article and how many components are present, the time required to reliably grade a single article could reach multiple hours. However, articles that clearly presented information took much less time. Even with the time necessary to grade each article, the authors found the FEMGP a useful and practical tool for assessing the reporting quality of published FE models.

5. Conclusion

The FEMGP provides a method for reviewers to judge the reporting quality of models submitted for publication and researchers a method for determining the items necessary for model development and reporting prior to submission. The FEMGP can be used to measure the overall reporting quality of the article, and assist researchers in reviewers in assessing the reliability, validity, and reproducibility of the FE model.

Acknowledgements

Funding

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Appendix A

We are attaching to our submission a blank copy of the Finite Element Model Grading Procedure (FEMGP) proposed by Erdemir et al. (2012). If using the FEMGP please cite as:

Erdemir, A., Guess, T.M., Halloran, J., Tadeipalli, S.C., Morrison, T.M., 2012. Considerations for reporting finite element analysis studies in biomechanics. *J. Biomech.* 45, 625–633. <https://doi.org/10.1016/j.jbiomech.2011.11.038>

**REPORTING PARAMETERS FOR
FINITE ELEMENT ANALYSIS STUDIES IN BIOMECHANICS**

Document: _____

- for description of individual items refer to the manuscript
- provide a summary if checked (Yes) for Reported

Group 1: Model Identification		
ITEM	REPORTED Yes No	SUMMARY
Model name		
Model keywords		
Version		
Physiological domain		
Mechanical domain		
Structure of interest		
Demographics		
State of represented organism		
Disease state		
Spatial scale		
Time scale		
Primary utility		
Secondary utility		
Primary highlight		
Secondary highlight		
Primary limitation		
Secondary limitation		
Reference to publication(s)		
Pointer to publication		
Related models		

Group 2: Model Structure		
ITEM	REPORTED Yes No	SUMMARY
Loading and boundary conditions		
for each, fill in form <i>Reporting Parameters for Loading and Boundary Conditions</i>		
Primary output variables		
Secondary output variables		
Source of anatomy		
Modality		
Resolution		
Reference configuration		
Subcomponents (subsidiary models)		
for each, fill in form <i>Reporting Parameters for Subcomponents</i>		
Interactions		
for each, fill in form <i>Reporting Parameters for Interactions</i>		

Group 3: Simulation Structure		
ITEM	REPORTED Yes No	SUMMARY
Name of simulation software		
Version of simulation software		
Solution strategy		
Numerical algorithms		
Convergence criteria		
Post-processing		

Group 4: Verification		
ITEM	REPORTED Yes No	SUMMARY
Methods of verification		
Correctness of formulation		
Comparisons with known solutions		
Sensitivity to simulation settings		
Mesh convergence		
Assessment of repeatability		

Group 5: Validation		
ITEM	REPORTED Yes No	SUMMARY
Validation procedure		
Validated output		
Overall modeling assumptions		
Physiological relevance of loading and boundary conditions		
Justification of parameters		
Data used for model development		
Data used for model comparison		
Sensitivity analysis		
Predictive capacity		

Group 6: Availability		
ITEM	REPORTED Yes No	SUMMARY
Contact		
Licensing		
Website for downloads		
Website for development		
Website for public commentary, responses and rating		

REPORTING PARAMETERS FOR LOADING AND BOUNDARY CONDITIONS		
<ul style="list-style-type: none"> • please fill in a new form for each loading and boundary condition • for description of individual items refer to the manuscript • provide a summary if checked (Yes) for Reported 		
Group 2: Model Structure - Loading and Boundary Conditions		
ITEM	REPORTED Yes No	SUMMARY
Type		
Region		
Magnitude and direction		
Time history		
REPORTING PARAMETERS FOR SUBCOMPONENTS		
<ul style="list-style-type: none"> • please fill in a new form for each subcomponent • for description of individual items refer to the manuscript • provide a summary if checked (Yes) for Reported 		
Group 2: Model Structure - Subcomponents		
ITEM	REPORTED Yes No	SUMMARY
Name		
Geometric representation		
Source		
Resolution		
Segmentation procedure		
Representative geometry		
Mesh		
Element name		
Element shape		
Element formulation		
Mesh density		
Constitutive representation		
Formulation		
Coefficients		
Source		
Reference configuration		
Other properties		
REPORTING PARAMETERS FOR INTERACTIONS		
<ul style="list-style-type: none"> • please fill in a new form for each interaction • for description of individual items refer to the manuscript • provide a summary if checked (Yes) for Reported 		
Group 2: Model Structure - Interactions		
ITEM	REPORTED Yes No	SUMMARY
Interacting components		
Interaction type		
Interaction formulation		
Interaction properties		

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Fig. 1.

Total available PubMed publications (29,320) for the search term "Finite Element" in PubMed (www.pubmed.org). This search was conducted on 05/31/2018. Since the early 2000's there has been an exponential growth in the number of available finite element publications.

Fig. 2. Results from the literature search within PubMed, Web of Science, and Embase. A total of 22 relevant articles met the inclusion/exclusion criterion.

Fig. 3. Histogram results showing the distribution of cumulative Finite Element Model Grading Procedure (FEMGP) scores. The quality ranges were characterized as “exceptional” (far right; $N=5$), “good” (mid right; $N=16$), “fair” (mid left; $N=1$), and “poor” (far left; $N=0$).

Fig. 4. Results comparing FEMGP scores of articles published before 2010 (left bar; mean = 62%, SD = 9%, $N=13$) and after 2010 (right bar; mean = 67%, SD = 11%, $N=9$). There was found to be no significant difference between the two groups ($p = .32$).

Fig. 5.

Results showing number of items satisfied within the groups Verification (top) and Validation (bottom) for all articles. The x-axis corresponds to the number of items satisfied out of 6 items for verification and out of 9 items for validation. The y-axis corresponds to the number of articles that satisfied that number of verification or validation items. Only 10 models satisfied 50% or more of the items within verification and only 9 articles met over 50% of the required items for validation.

Table 1

Studies included in the literature review and graded using the Finite Element Model Grading Procedure (FEMGP) proposed by Erdemir et al. (2012).

Author	Study type	Region of interest	Model identification	Model structure	Simulation structure	Verification	Validation	Availability	Loading/ boundary conditions	Sub-components	Interactions	Cumulative
(Adams et al., 2007)	Clinical	Rotator cuff	94%	100%	100%	67%	100%	20%	100%	88%	100%	85% (Exceptional)
(Büchler et al., 2002a)	Clinical	Shoulder joint	72%	100%	100%	50%	33%	20%	50%	88%	75%	65% (Good)
(Büchler et al., 2002b)	Clinical	Shoulder joint	70%	100%	100%	50%	33%	20%	75%	94%	75%	69% (Good)
(Büchler and Farron, 2004)	Implant	Shoulder joint	70%	100%	100%	50%	33%	20%	75%	94%	75%	69% (Good)
(Celemín et al., 2014)	Tear	Supraspinatus tendon	72%	56%	67%	50%	33%	20%	50%	71%	75%	55% (Good)
(Engelhardt et al., 2016)	Tear	Supraspinatus tendon	89%	100%	83%	67%	56%	20%	75%	88%	100%	75% (Exceptional)
(Farron et al., 2006)	Implant	Shoulder joint	70%	100%	100%	50%	33%	20%	75%	94%	75%	69% (Good)
(Funakoshi et al., 2008)	Suture repair	Rotator cuff	85%	78%	33%	17%	33%	20%	75%	65%	75%	53% (Good)
(Inoue et al., 2013)	Clinical	Supraspinatus tendon	89%	89%	50%	33%	33%	20%	75%	76%	75%	60% (Good)
(Iwamoto et al., 2000)	Crash	Shoulder joint	72%	67%	50%	33%	56%	20%	100%	71%	100%	63% (Good)
(Iwamoto et al., 2001)	Crash	Shoulder joint	72%	67%	50%	33%	56%	20%	100%	71%	100%	63% (Good)
(Jang et al., 2015)	Clinical	Rotator cuff	83%	100%	33%	17%	44%	20%	75%	65%	75%	57% (Good)
(Luo et al., 1998)	Tear	Supraspinatus tendon	83%	78%	50%	0%	33%	20%	75%	53%	50%	49% (Fair)
(Mantovani et al., 2016)	Suture repair	Supraspinatus tendon	78%	100%	50%	33%	33%	20%	75%	76%	75%	60% (Good)
(Quental et al., 2016)	Tear	Supraspinatus tendon	89%	100%	67%	67%	67%	20%	100%	100%	100%	79% (Exceptional)
(Sano et al., 2006)	Tear	Supraspinatus tendon	89%	78%	33%	17%	33%	20%	75%	65%	100%	57% (Good)
(Sano et al., 2007)	Tear	Supraspinatus tendon	89%	78%	33%	17%	33%	20%	75%	65%	100%	57% (Good)

Author	Study type	Region of interest	Model identification	Model structure	Simulation structure	Verification	Validation	Availability	Loading/ boundary conditions	Sub-components	Interactions	Cumulative
(Sano et al., 2013)	Tear	Supraspinatus tendon	89%	100%	33%	17%	33%	20%	75%	76%	75%	58% (Good)
(Seki et al., 2008)	Clinical	Supraspinatus tendon	89%	78%	33%	17%	44%	20%	75%	76%	100%	59% (Good)
(Thunes et al., 2015)	Tear	Supraspinatus tendon	72%	100%	100%	67%	100%	20%	75%	82%	100%	80% (Exceptional)
(Wakabayashi et al., 2003)	Clinical	Supraspinatus tendon	89%	78%	33%	17%	33%	20%	75%	65%	75%	54% (Good)
(Webb et al., 2014)	Clinical	Shoulder joint	94%	100%	83%	50%	89%	20%	75%	94%	100%	78% (Exceptional)
Overall category means			82%	88%	63%	37%	47%	20%	77%	78%	85%	-