



Hybrid discrete and finite element analysis enables fast evaluation of hip joint cartilage mechanical response

Mikko S. Venäläinen^{a,b,*}, Mao Li^a, Juha Töyräs^{a,c,d}, Rami K. Korhonen^c, Jurgen Fripp^{a,e}, Stuart Crozier^a, Shekhar S. Chandra^a, Craig Engstrom^f

^a School of Electrical Engineering and Computer Science, The University of Queensland, Brisbane, Australia

^b Department of Medical Physics, Turku University Hospital and University of Turku, Turku, Finland

^c Department of Technical Physics, University of Eastern Finland, Kuopio, Finland

^d Science Service Center, Kuopio University Hospital, Kuopio, Finland

^e The Australian e-Health Research Centre, CSIRO Health and Biosecurity, Brisbane, Australia

^f School of Human Movement Studies, The University of Queensland, Brisbane, Australia

ARTICLE INFO

Keywords:

Discrete element analysis
Finite element analysis
Hip joint
Articular cartilage
Mechanical stress

ABSTRACT

Finite element analysis (FEA) is the leading numerical technique for studying joint biomechanics related to the onset and progression of osteoarthritis. However, subject-specific FEA of joint mechanics is a time- and compute-intensive process limiting its clinical applicability. We introduce and evaluate a novel hybrid modelling framework combining discrete element analysis (DEA) and FEA for computationally efficient evaluation of cartilage mechanics in the hip joint. In our approach, the hip joint contact mechanics are first estimated using DEA and subsequently used as input for matching FEA models, substantially reducing model complexity. The cartilage mechanical responses obtained using the hybrid DEA-FEA method were evaluated for subject-specific hip joint geometries from five asymptomatic individuals under loading conditions typical to normal walking gait and compared to conventional FEA in terms of peak intra-tissue mechanical stresses and model run-times. The hybrid DEA-FEA method had a median run-time of 3.6 min per subject (64-core processor, 512 GB RAM) and produced minimum principal (compressive) stress estimates comparable to stresses obtained using conventional FEA models with a median run-time of 96.2 min. On average, the peak compressive stresses obtained using the hybrid DEA-FEA approach were 0.06 MPa (95 % confidence interval: -0.86 – 0.99) lower than the stresses estimated with conventional FEA. Despite up to 1.4 MPa differences at individual gait time-points, the results indicate that the proposed hybrid DEA-FEA method enables estimation of hip cartilage mechanics in a fraction of time compared to conventional FEA, facilitating implementation in large cohort studies and clinical applications.

1. Introduction

The hip joint is commonly affected by osteoarthritis (OA), a debilitating condition leading to progressive degeneration of articular cartilage, chronic pain, and reduced mobility (Zhang and Jordan, 2010). Tissue damage associated with provocative mechanical loading in cartilage plays an important role in OA onset and progression (Felson, 2013; Guilak, 2011; Wilson et al., 2006). As direct experimental characterization of *in vivo* stresses and strains in human joints is generally impractical or limited (e.g., arthroplasty patients), several computational approaches have been applied to estimate joint biomechanics

non-invasively.

Finite element analysis (FEA) is a popular computational technique for evaluating joint and soft-tissue biomechanics under normal and pathological conditions (Cannon et al., 2023; Henak et al., 2014; Kitamura et al., 2022; Liukkonen et al., 2017; Mononen et al., 2016; Ng et al., 2016; Venäläinen et al., 2016). Combined with advanced material models for articular cartilage, FEA can also be used for predicting OA progression (Liukkonen et al., 2017; Mononen et al., 2016; Orozco et al., 2018). In large cohort studies, the main limitation of FEA is its labour-intensive and computationally expensive nature.

Discrete element analysis (DEA) is a fast and computationally

* Corresponding author at: Department of Medical Physics, Turku University Hospital and University of Turku, Kiinamyllynkatu 4–8, Turku, P.O. Box 52, FI-20521 Turku, Finland.

E-mail address: mikko.venalainen@utu.fi (M.S. Venäläinen).

<https://doi.org/10.1016/j.jbiomech.2025.112568>

Accepted 3 February 2025

Available online 6 February 2025

0021-9290/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

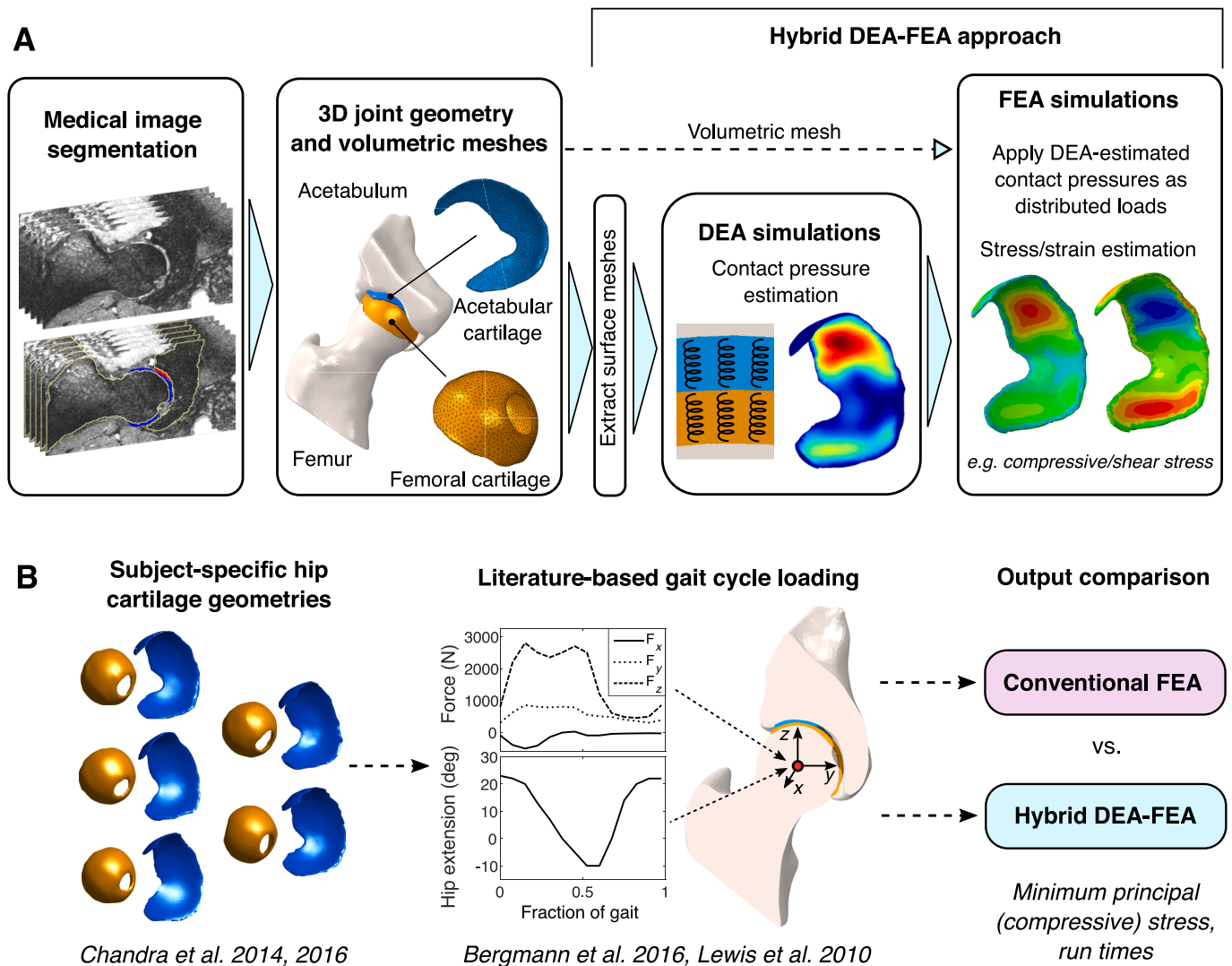


Fig. 1. Study overview. **A)** The framework for the hybrid discrete element analysis (DEA) and finite element analysis (FEA) pipeline for evaluating hip cartilage biomechanics. The key difference compared to conventional FEA is the initial estimation of contact pressures with DEA and using them as input loads for FEA thus removing the need for contact analysis and reducing run times. **B)** The performance of the combined DEA-FEA approach was evaluated by performing gait simulations for five subject-specific hip cartilage geometries and comparing the obtained mechanical stresses and run times with those from conventional FEA.

inexpensive method for estimating joint contact mechanics (Abraham et al., 2013; Aitken et al., 2024; Anderson et al., 2010; Chao et al., 2010; Goetz et al., 2023; Li et al., 2021; Townsend et al., 2018). Previously, we demonstrated that DEA provides similar estimations of hip joint contact mechanics compared to FEA (Li et al., 2021). In contrast to continuum mechanics, in DEA, articulating surfaces are modelled as an array of compressive-only springs and contact stresses are approximated via spring deformation resulting from applied forces (Chao et al., 2010; Genda et al., 2001), enabling the estimation of joint contact mechanics in a fraction of time compared to FEA. However, with its focus on contact mechanics, DEA alone can provide only limited insights into biomechanical factors potentially associated with OA progression as compared to intra-tissue stresses, strains, and fluid pressures readily estimated in FEA (Eskelinen et al., 2019; Hosseini et al., 2014; Mononen et al., 2016; Orozco et al., 2018; Párraga Quiroga et al., 2017).

Here, we introduce a novel hybrid pipeline applying both DEA and FEA techniques sequentially to achieve fast estimation of cartilage mechanical response. We hypothesize this modelling pipeline is computationally highly efficient and produces comparable results with conventional FEA. This study investigates the performance of the hybrid DEA-FEA approach in gait simulations using biomechanical hip joint

models with subject-specific geometry and compares results with those from conventional FEA.

2. Methods

2.1. Study subjects

Magnetic resonance (MR) images (3D true fast imaging with steady-state free precession sequence, 3 T Siemens Magnetom Trio, Germany) from five asymptomatic individuals were utilized from a previous study (Xia et al., 2014). The University of Queensland Human Research Committee approved the research (approval number: 2018000405).

2.2. Segmentation and model geometries

Consistent with our previous study (Li et al., 2021), hip cartilage was segmented from MR images using validated automatic techniques (Chandra et al., 2014, 2016). Then, using a custom MATLAB (Mathworks, MA, USA) script, volumetric cartilage meshes (quadratic tetrahedral elements with target edge lengths of ~ 1.6 mm and ~ 1.1 mm for femoral and acetabular cartilage, respectively) were generated using the

built-in generateMesh function from the Partial Differential Equation Toolbox. Based on the volumetric meshes, for DEA, matching surface meshes were generated in STL format.

2.3. Gait cycle loading

As per our previous work (Li et al., 2021), the hip joint models were subjected to gait cycle loading derived from the literature. This included standardized hip joint loads along x , y , and z axes from a previous *in-vivo* experimental study (Bergmann et al., 2016), and flexion–extension rotation, estimated using a musculoskeletal model (Lewis et al., 2010). The remaining rotational degrees of freedom, namely internal–external and abduction–adduction rotational movements, were restrained during loading. The boundary conditions were applied to a reference point, located at the femoral head centre and kinematically coupled with the femoral cartilage–bone interface, while keeping the acetabular cartilage–bone interface fixed in all directions. As in our previous study (Li et al., 2021), the gait cycle was discretized into 13 evenly spaced time-points that captured all the main phases of the gait cycle for comparison of modelling outputs. All simulations were performed on the same PC workstation (AMD Ryzen Threadripper PRO 3995WX 64-core processor, 2.7 GHz, 512 GB RAM). For comparison of run-times between approaches, only a single thread was used.

2.4. Hybrid DEA-FEA workflow

The concept of the hybrid DEA-FEA approach is to use DEA and FEA sequentially to combine advantages of both techniques, resulting in fast estimation of intra-tissue stresses and strains in hip cartilage (Fig. 1A). The entire hybrid pipeline, from initial mesh generation to FEA simulations was implemented in custom MATLAB code.

First, using STL representations of femoral and acetabular cartilage, DEA was applied to obtain contact pressure estimates on the acetabular contact surface at each time-point of the gait cycle. We used a previous formulation for spring stiffness:

$$K_i = \frac{E(1-\nu)S_i}{(1-2\nu)(1+\nu)h_i} \alpha^{d_i/h_i} \quad (1)$$

where i is the i^{th} spring, E is Young's modulus, ν is Poisson's ratio, S_i is the area of the triangular cell where the spring attached, h_i is the sum of acetabular and femoral cartilage thicknesses, d_i is the compression displacement and α is an empirical coefficient (Li et al., 2021). Previously, the contact mechanics (contact pressures and areas) estimated using this implementation during gait were found to be in line with prior reports (Armiger et al., 2009; Harris et al., 2012; Li et al., 2021). The nonlinear factor α^{d_i/h_i} is a penalty function applied to improve contact pressure estimation with subject-specific geometries by exponentially increasing or decreasing spring stiffness with increasing compression displacement. Here, a constant value of $\alpha = 0.85$ was used.

Next, the obtained contact pressures were used as distributed pressure loads for the acetabular contact surface to finally obtain stress and strain estimations using static FEA. These models included only acetabular cartilage and did not involve contact modelling, thus having substantially reduced model complexity. For FEA simulations, Abaqus/Standard 2020 (Dassault Systèmes SIMULIA Corp., RI, USA) solver was used. In all simulations, articular cartilage was modelled as a linear elastic material with Young's modulus $E = 10\text{MPa}$ and Poisson's ratio $\nu = 0.43$ (Abraham et al., 2013; Richard et al., 2013; Shepherd and Seedhom, 1999).

2.5. Conventional FEA

In walking gait simulations analysed using conventional FEA, both femoral and acetabular cartilage were modelled. Simulations were completed in a single run by applying complete waveforms of extracted

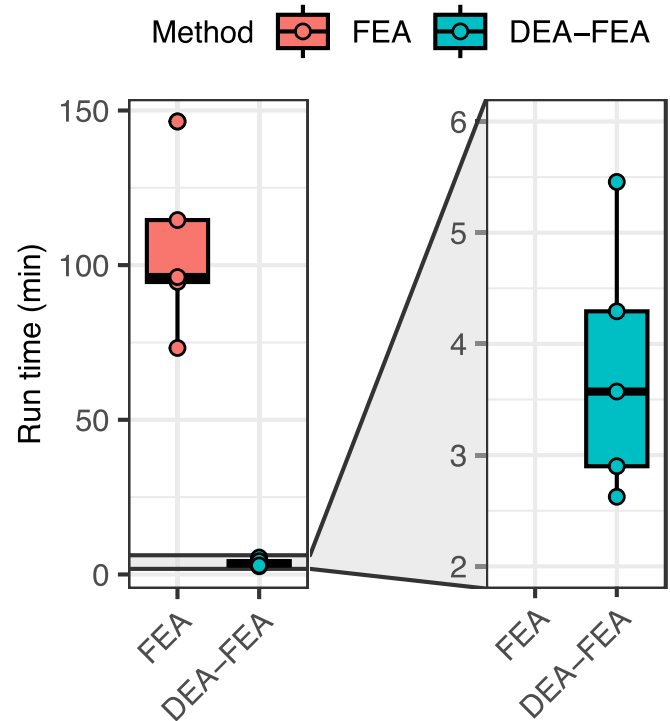


Fig. 2. Gait simulation times for conventional finite element analysis (FEA) models, and the proposed hybrid discrete element analysis (DEA)-FEA models.

gait data as time-varying loading and boundary conditions. The cartilage-to-cartilage contact was assumed to be frictionless and modelled using a hard pressure-overclosure relationship and surface-to-surface discretization. The models, having the same material properties as in the hybrid DEA-FEA method, were constructed from the previously generated volumetric meshes using a custom MATLAB script and ran using the same FEA solver. Mesh convergence was checked by reanalysis with $> 50\%$ denser meshes, which yielded differences of $< 3\%$ in peak stresses.

2.6. Data analysis

Data for the estimated cartilage mechanical responses were reported in terms of minimum principal (compressive) stresses, since peak stresses generated in isotropic elastic cartilage during gait are primarily compressive, as demonstrated previously for the knee (Klets et al., 2016). The resulting stress distributions were visualized using Abaqus/CAE software and extracted for further analysis and numerical comparison in R statistical computing environment version 4.0.3 (R Core Team, 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Austria. URL <https://www.R-project.org/>) (Fig. 1B). Analysis of peak stress values across subjects and time-points was undertaken using a Bland-Altman plot. R package ggplot2 (Wickham, 2016) was used for visualizations.

3. Results

The median calculation time to complete gait simulations for a single subject was 96.2 min (range: 73.2–146.5) with conventional FEA and 3.6 min (range: 2.6–5.5) with the hybrid DEA-FEA approach (Fig. 2). In the hybrid DEA-FEA approach, the median calculation times of the embedded DEA and FEA simulations per subject were 1.2 min (range: 1.0–2.1) and 2.1 min (range: 1.4–3.4), respectively.

The calculated distributions of minimum principal (compressive) stresses and locations of peak stress during the gait cycle were similar between the conventional FEA and hybrid DEA-FEA approaches both on

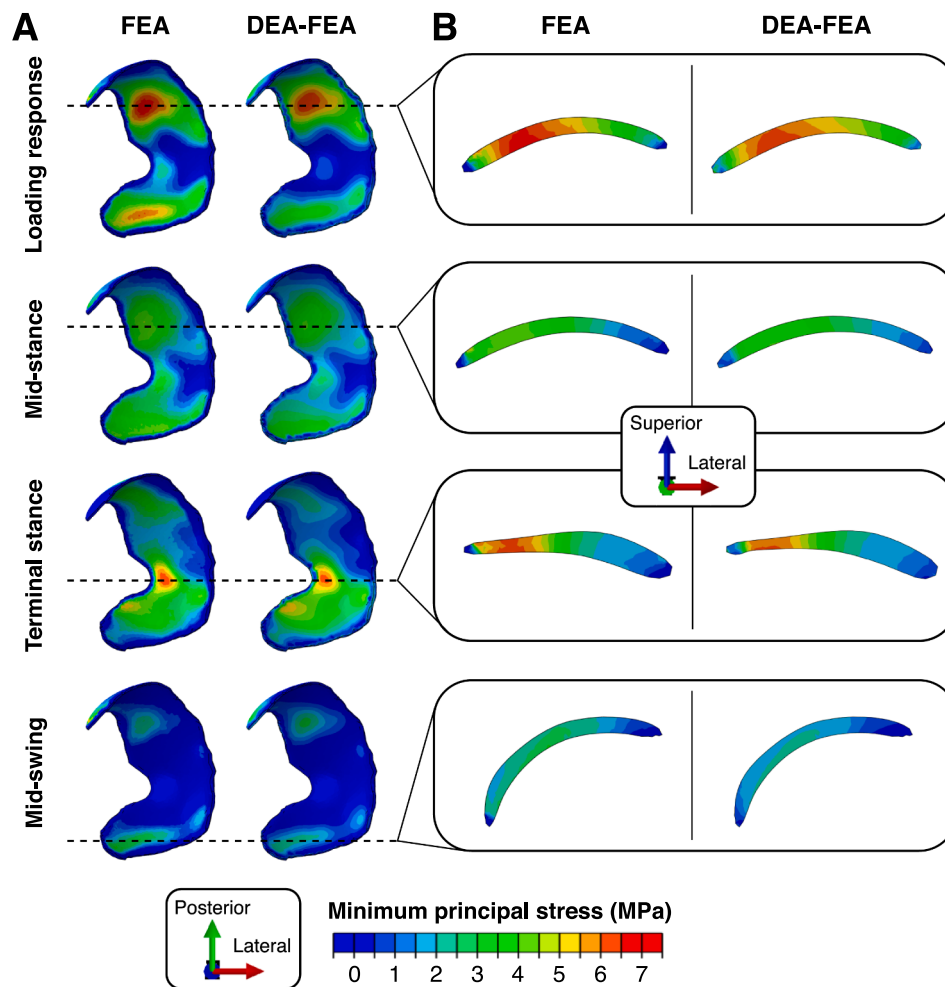


Fig. 3. Minimum principal (compressive) stress distributions estimated in acetabular cartilage using both conventional finite element analysis (FEA) and the proposed hybrid discrete element analysis (DEA)-FEA approach. Example distributions are given for Subject 1 during different phases of the gait cycle **A**) on acetabular contact surface and **B**) through cartilage thickness of the coronal section with maximum compressive stress.

the acetabular contact surface (see Fig. 3A for example distributions of compressive stresses for Subject 1) and through the cartilage thickness (Fig. 3B). For the FEA and DEA-FEA modelling, the basic patterns, including the biphasic impact and propulsive peaks, and values of peak compressive stresses were similar throughout the gait cycle for all subjects (Fig. 4A). Both methods calculated the maximum peak compressive stress during stance phase of gait to be between 6 to 8 MPa for subjects 1, 2, 3 and 4, and between 9 to 10 MPa for subject 5. The largest difference of 1.4 MPa in peak compressive stresses between the two methods was observed during terminal stance for subject 4. Across all time-points and subjects, on average, the peak stresses estimated using the hybrid DEA-FEA were 0.06 MPa (95 % confidence interval: $-0.86-0.99$) lower than with conventional FEA (Fig. 4B).

4. Discussion

In this study, we introduced a novel hybrid DEA-FEA approach for fast calculation of cartilage mechanical response in the hip joint under dynamic physiological loading during the walking gait cycle. Compared to conventional FEA, the hybrid DEA-FEA method produced similar estimates of minimum principal (compressive) stress calculations in cartilage in subject-specific hip joint geometries but with substantially shorter simulation run-times (minutes versus hours), confirming our hypothesis.

The proposed hybrid DEA-FEA approach is a new addition to the family of methods aiming to facilitate the use of subject-specific FEA in

time-sensitive analyses such as those applied to large clinical cohorts. Other previously proposed methods to accelerate FEA of cartilage mechanics include *e.g.* template-based or statistical shape modelling (Esrafilian et al., 2024; Mononen et al., 2019; Van Houcke et al., 2020) which, at present, are applicable only to morphologically normal subjects.

The key solution to reduce computation time in the hybrid DEA-FEA approach was the replacement of contact modelling in FEA with computationally efficient DEA and using the obtained contact pressure estimates as input for simplified FEA models. This efficiently reduced FEA model complexity and averted any convergence issues typically associated with contact modelling in FEA model development. The stress distributions obtained using the DEA-FEA approach followed closely the DEA-based contact pressure patterns indicating that any deviations in stress between DEA-FEA and FEA arose mainly from intrinsic differences between the contact estimation algorithms. Therefore, if DEA, or any other computationally robust solution, would be able to produce matching contact pressures with FEA, the stress estimates obtained with the hybrid approach would be close to identical. Regardless, despite FEA being a well-established method in the field, there exists no “gold-standard” computational tool for contact pressure estimation and hence minor deviations between the approaches were considered acceptable.

The main limitation in our present analysis was that the sensitivity of the hybrid DEA-FEA method was evaluated only in terms of varying tissue geometry of asymptomatic individuals and further sensitivity and validation analyses are warranted to verify the suitability of the method

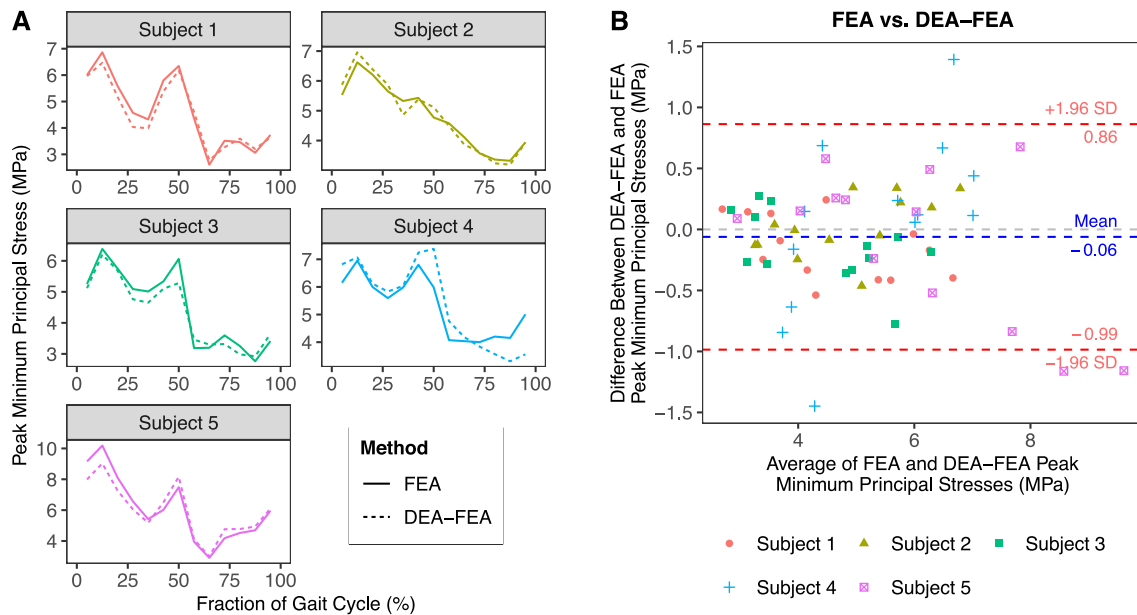


Fig. 4. Comparison of peak values of minimum principal (compressive) stresses obtained using conventional finite element analysis (FEA) and the proposed hybrid discrete element analysis (DEA)-FEA approach. **A)** The peak compressive stress values are visualized throughout the gait cycle for all subjects and **B)** compared in 13 time-points during the gait cycle between the methods using a Bland-Altman plot. Positive difference in Bland-Altman plot indicates that a higher stress value was estimated using DEA-FEA approach compared to conventional FEA.

for large-scale applications. Firstly, we used simplified material properties for cartilage which did not take into account the porous, visco-elastic nature of the tissue (Julkunen et al., 2007; Korhonen et al., 2003; Wilson et al., 2004) important for predicting cartilage degeneration (Eskelinen et al., 2019; Mononen et al., 2016; Orozco et al., 2018). Secondly, only one set of boundary conditions was applied and further simulations using more refined subject-specific data, including secondary kinematics, should be performed. Lastly, the applicability of the DEA-FEA method should be verified on subjects with different joint pathologies, specifically those affecting hip morphology.

In conclusion, the proposed hybrid DEA-FEA method produced estimations of cartilage mechanical response comparable to conventional FEA but took substantially less time to compute. In future, when validated with more advanced material models, subject-specific loading data, and different joint pathologies, the method may provide novel opportunities to further promote OA research as well as develop and more readily embed joint biomechanical models into clinically applicable tools.

CRedit authorship contribution statement

Mikko S. Venäläinen: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mao Li:** Writing – review & editing, Software, Methodology, Investigation, Data curation, Conceptualization. **Juha Töyräs:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Rami K. Korhonen:** Writing – review & editing, Supervision, Investigation. **Jurgen Fripp:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Stuart Crozier:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Shekhar S. Chandra:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Craig Engstrom:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported under the Australian National Health and Medical Research Council Development and Ideas Grants (grant numbers APP1139868 and APP2001734). Dr. Venäläinen received funding from the Academy of Finland (grant number 322123) during the course of the study. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. CSC – IT Center for Science, Finland, is acknowledged for providing computational resources and software for this work.

References

- Abraham, C.L., Maas, S.A., Weiss, J.A., Ellis, B.J., Peters, C.L., Anderson, A.E., 2013. A new discrete element analysis method for predicting hip joint contact stresses. *J. Biomech.* 46, 1121–1127. <https://doi.org/10.1016/j.jbiomech.2013.01.012>.
- Aitken, H.D., Goetz, J.E., Glass, N.A., Miller, A., Rivas, D.J.L., Westermann, R.W., McKinley, T.O., Willey, M.C., 2024. Persistently elevated joint contact stress after periacetabular osteotomy is associated with joint failure at minimum 10-year follow-up. *J. Orthop. Res.* 42, 2773–2783. <https://doi.org/10.1002/jor.25935>.
- Anderson, D.D., Iyer, K.S., Segal, N.A., Lynch, J.A., Brown, T.D., 2010. Implementation of discrete element analysis for subject-specific, population-wide investigations of habitual contact stress exposure. *J. Appl. Biomech.* 26, 215–223. <https://doi.org/10.1123/jab.26.2.215>.
- Armiger, R.S., Armand, M., Tallroth, K., Lepistö, J., Mears, S.C., 2009. Three-dimensional mechanical evaluation of joint contact pressure in 12 periacetabular osteotomy patients with 10-year follow-up. *Acta Orthop.* 80, 155–161. <https://doi.org/10.3109/17453670902947390>.
- Bergmann, G., Bender, A., Dymke, J., Duda, G., Damm, P., 2016. Standardized loads acting in hip implants. *PLoS One* 11, e0155612.
- Cannon, J., Rankin, J.W., Lewton, K.L., Liu, J., Powers, C.M., 2023. Femoral and acetabular features explain acetabular contact pressure sensitivity to hip internal rotation in persons with cam morphology: a finite element analysis. *Clin. Biomech.* 107, 106025. <https://doi.org/10.1016/j.clinbiomech.2023.106025>.
- Chandra, S.S., Xia, Y., Engstrom, C., Crozier, S., Schwarz, R., Fripp, J., 2014. Focused shape models for hip joint segmentation in 3D magnetic resonance images. *Med. Image Anal.* 18, 567–578. <https://doi.org/10.1016/j.media.2014.02.002>.

- Chandra, S.S., Surowiec, R., Ho, C., Xia, Y., Engstrom, C., Crozier, S., Frupp, J., 2016. Automated analysis of hip joint cartilage combining MR T2 and three-dimensional fast-spin-echo images. *Magn. Reson. Med.* 75, 403–413. <https://doi.org/10.1002/mrm.25598>.
- Chao, E.Y.S., Volokh, K.Y., Yoshida, H., Shiba, N., Ide, T., 2010. Discrete element analysis in musculoskeletal biomechanics. *Mol. Cell. Biomech.* 7, 175–192.
- Eskelinen, A.S.A., Mononen, M.E., Venäläinen, M.S., Korhonen, R.K., Tanska, P., 2019. Maximum shear strain-based algorithm can predict proteoglycan loss in damaged articular cartilage. *Biomech. Model. Mechanobiol.* 18, 753–778. <https://doi.org/10.1007/s10237-018-01113-1>.
- Esrifiliani, A., Chandra, S.S., Gatti, A.A., Nissi, M., Mustonen, A.-M., Saisanen, L., Reijonen, J., Nieminen, P., Julkunen, P., Toyras, J., Saxby, D.J., Lloyd, D.G., Korhonen, R.K., 2024. An Automated and Robust Tool for Musculoskeletal and Finite Element Modeling of the Knee Joint. *IEEE Trans Biomed Eng PP*. <https://doi.org/10.1109/TBME.2024.3438272>.
- Felson, D.T., 2013. Osteoarthritis as a disease of mechanics. *Osteoarthritis Cartilage* 21, 10–15. <https://doi.org/10.1016/j.joca.2012.09.012>.
- Genda, E., Iwasaki, N., Li, G., MacWilliams, B.A., Barrance, P.J., Chao, E.Y., 2001. Normal hip joint contact pressure distribution in single-leg standing—effect of gender and anatomic parameters. *J. Biomech.* 34, 895–905. [https://doi.org/10.1016/s0021-9290\(01\)00041-0](https://doi.org/10.1016/s0021-9290(01)00041-0).
- Goetz, J.E., Thomas-Aitken, H.D., Sittou, S.E., Westermann, R.W., Willey, M.C., 2023. Joint contact stress improves in dysplastic hips after periacetabular osteotomy but remains higher than in normal hips. *Hip Int.* 33, 298–305. <https://doi.org/10.1177/11207000211036414>.
- Guilak, F., 2011. Biomechanical factors in osteoarthritis. *Best Pract. Res. Clin. Rheumatol.* 25, 815–823. <https://doi.org/10.1016/j.berh.2011.11.013>.
- Harris, M.D., Anderson, A.E., Henak, C.R., Ellis, B.J., Peters, C.L., Weiss, J.A., 2012. Finite element prediction of cartilage contact stresses in normal human hips. *J. Orthop. Res.* 30, 1133–1139. <https://doi.org/10.1002/jor.22040>.
- Henak, C.R., Ateshian, G.A., Weiss, J.A., 2014. Finite element prediction of transchondral stress and strain in the human hip. *J. Biomech. Eng.* 136, 021021. <https://doi.org/10.1115/1.4026101>.
- Hosseini, S.M., Wilson, W., Ito, K., van Donkelaar, C.C., 2014. A numerical model to study mechanically induced initiation and progression of damage in articular cartilage. *Osteoarthritis Cartilage* 22, 95–103. <https://doi.org/10.1016/j.joca.2013.10.010>.
- Julkunen, P., Kiviranta, P., Wilson, W., Jurvelin, J.S., Korhonen, R.K., 2007. Characterization of articular cartilage by combining microscopic analysis with a fibril-reinforced finite-element model. *J. Biomech.* 40, 1862–1870. <https://doi.org/10.1016/j.jbiomech.2006.07.026>.
- Kitamura, K., Fujii, M., Iwamoto, M., Ikemura, S., Hamai, S., Motomura, G., Nakashima, Y., 2022. Is Anterior Rotation of the Acetabulum Necessary to Normalize Joint Contact Pressure in Periacetabular Osteotomy? A Finite-element Analysis Study. *Clin. Orthop. Relat. Res.* 480, 67–78. <https://doi.org/10.1097/CORR.0000000000001893>.
- Klets, O., Mononen, M.E., Tanska, P., Nieminen, M.T., Korhonen, R.K., Saarakkala, S., 2016. Comparison of different material models of articular cartilage in 3D computational modeling of the knee: Data from the Osteoarthritis Initiative (OAI). *J. Biomech.* 49, 3891–3900. <https://doi.org/10.1016/j.jbiomech.2016.10.025>.
- Korhonen, R.K., Laasanen, M.S., Töyräs, J., Lappalainen, R., Helminen, H.J., Jurvelin, J.S., 2003. Fibril reinforced poroelastic model predicts specifically mechanical behavior of normal, proteoglycan depleted and collagen degraded articular cartilage. *J. Biomech.* 36, 1373–1379. [https://doi.org/10.1016/s0021-9290\(03\)00069-1](https://doi.org/10.1016/s0021-9290(03)00069-1).
- Lewis, C.L., Sahrman, S.A., Moran, D.W., 2010. Effect of hip angle on anterior hip joint force during gait. *Gait Posture* 32, 603–607. <https://doi.org/10.1016/j.gaitpost.2010.09.001>.
- Li, M., Venäläinen, M.S., Chandra, S.S., Patel, R., Frupp, J., Engstrom, C., Korhonen, R.K., Töyräs, J., Crozier, S., 2021. Discrete element and finite element methods provide similar estimations for hip joint contact mechanics during walking gait. *J. Biomech.* 115, 110163. <https://doi.org/10.1016/j.jbiomech.2020.110163>.
- Liukkonen, M.K., Mononen, M.E., Klets, O., Arokoski, J.P., Saarakkala, S., Korhonen, R.K., 2017. Simulation of Subject-Specific Progression of Knee Osteoarthritis and Comparison to Experimental Follow-up Data: Data from the Osteoarthritis Initiative. *Sci. Rep.* 7, 9177. <https://doi.org/10.1038/s41598-017-09013-7>.
- Mononen, M.E., Tanska, P., Isaksson, H., Korhonen, R.K., 2016. A Novel Method to Simulate the Progression of Collagen Degeneration of Cartilage in the Knee: Data from the Osteoarthritis Initiative. *Sci. Rep.* 6, 21415. <https://doi.org/10.1038/srep21415>.
- Mononen, M.E., Liukkonen, M.K., Korhonen, R.K., 2019. Utilizing Atlas-Based Modeling to Predict Knee Joint Cartilage Degeneration: Data from the Osteoarthritis Initiative. *Ann. Biomed. Eng.* 47, 813–825. <https://doi.org/10.1007/s10439-018-02184-y>.
- Ng, K.C.G., Lamontagne, M., Labrosse, M.R., Beaulé, P.E., 2016. Hip Joint Stresses Due to Cam-Type Femoroacetabular Impingement: A Systematic Review of Finite Element Simulations. *PLoS One* 11, e0147813.
- Orozco, G.A., Tanska, P., Florea, C., Grodzinsky, A.J., Korhonen, R.K., 2018. A novel mechanobiological model can predict how physiologically relevant dynamic loading causes proteoglycan loss in mechanically injured articular cartilage. *Sci. Rep.* 8, 15599. <https://doi.org/10.1038/s41598-018-33759-3>.
- Párraga Quiroga, J.M., Wilson, W., Ito, K., van Donkelaar, C.C., 2017. The effect of loading rate on the development of early damage in articular cartilage. *Biomech. Model. Mechanobiol.* 16, 263–273. <https://doi.org/10.1007/s10237-016-0815-0>.
- Richard, F., Villars, M., Thibaud, S., 2013. Viscoelastic modeling and quantitative experimental characterization of normal and osteoarthritic human articular cartilage using indentation. *J. Mech. Behav. Biomed. Mater.* 24, 41–52. <https://doi.org/10.1016/j.jmbm.2013.04.012>.
- Shepherd, D.E., Seedhom, B.B., 1999. The “instantaneous” compressive modulus of human articular cartilage in joints of the lower limb. *Rheumatology (Oxford)* 38, 124–132. <https://doi.org/10.1093/rheumatology/38.2.124>.
- Townsend, K.C., Thomas-Aitken, H.D., Rudert, M.J., Kern, A.M., Willey, M.C., Anderson, D.D., Goetz, J.E., 2018. Discrete element analysis is a valid method for computing joint contact stress in the hip before and after acetabular fracture. *J. Biomech.* 67, 9–17. <https://doi.org/10.1016/j.jbiomech.2017.11.014>.
- Van Houcke, J., Audenaert, E.A., Atkins, P.R., Anderson, A.E., 2020. A Combined Geometric Morphometric and Discrete Element Modeling Approach for Hip Cartilage Contact Mechanics. *Front. Bioeng. Biotechnol.* 8, 318. <https://doi.org/10.3389/fbioe.2020.00318>.
- Venäläinen, M.S., Mononen, M.E., Salo, J., Räsänen, L.P., Jurvelin, J.S., Töyräs, J., Virén, T., Korhonen, R.K., 2016. Quantitative Evaluation of the Mechanical Risks Caused by Focal Cartilage Defects in the Knee. *Sci. Rep.* 6, 37538. <https://doi.org/10.1038/srep37538>.
- Wickham, H., 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.
- Wilson, W., van Donkelaar, C.C., van Rietbergen, B., Ito, K., Huijkes, R., 2004. Stresses in the local collagen network of articular cartilage: a poroviscoelastic fibril-reinforced finite element study. *J. Biomech.* 37, 357–366. [https://doi.org/10.1016/s0021-9290\(03\)00267-7](https://doi.org/10.1016/s0021-9290(03)00267-7).
- Wilson, W., van Burken, C., van Donkelaar, C., Buma, P., van Rietbergen, B., Huijkes, R., 2006. Causes of mechanically induced collagen damage in articular cartilage. *J. Orthop. Res.* 24, 220–228. <https://doi.org/10.1002/jor.20027>.
- Xia, Y., Chandra, S.S., Engstrom, C., Strudwick, M.W., Crozier, S., Frupp, J., 2014. Automatic hip cartilage segmentation from 3D MR images using arc-weighted graph searching. *Phys. Med. Biol.* 59, 7245–7266. <https://doi.org/10.1088/0031-9155/59/23/7245>.
- Zhang, Y., Jordan, J.M., 2010. Epidemiology of osteoarthritis. *Clin. Geriatr. Med.* 26, 355–369. <https://doi.org/10.1016/j.cger.2010.03.001>.