Inverse Bone Remodelling

Towards Predicting the Hip Joint Pressure Distribution

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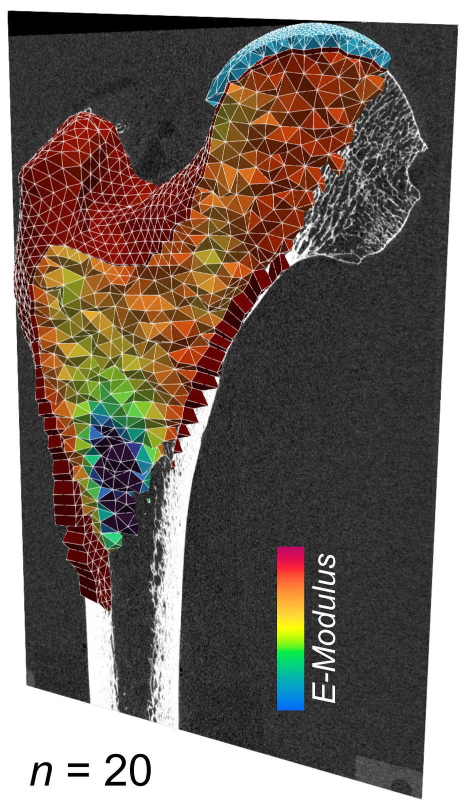
Motivation

Inverse bone remodelling (IBR) builds upon functional adaptation: Bone undergoes constant *(re)modelling*, i.e., new bone is formed in highly loaded regions and resorped in regions of no load. Thus, bone tissue strives for a *maximal homogeneously* loading. IBR tries to *invert* this process and predict the loading conditions that formed the adapted microstructure by applying a set of test loads on a finite element (FE) model. Therefore, IBR can be used to predict *patient-specific in vivo* loading conditions from CT images, e.g., to assess the individual fracture risk.

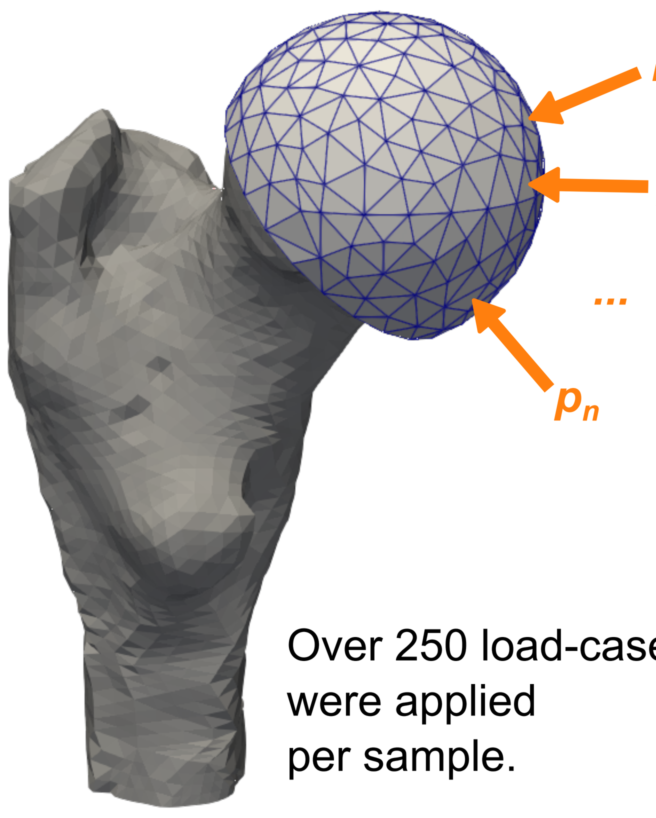
To overcome the requirement for micro-CT images, we recently developed a homogenized-FE (hFE) based IBR approach [1,2], which allows for faster prediction and the application of more test load-cases. However, using too many load-cases is known to lead to ambigous solutions [4]. Thus, we evaluated an alternative approach by using a *load case homogeneity score,* which is independent of load-case count. The goal of this study was to evaluate such a score and qualitatively compare the results to pressure distributions at the hip joint found in the literature.

Methods

Create Finite Element Model from µCT Data [1]



Discretize Cartilage Surface and Apply Unit Pressure on Each Facet

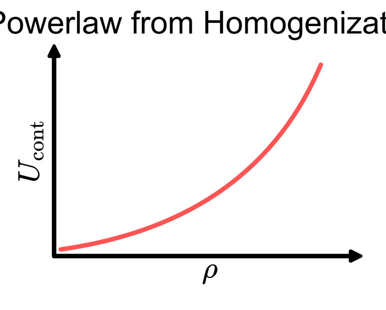


Over 250 load-cases were applied per sample.

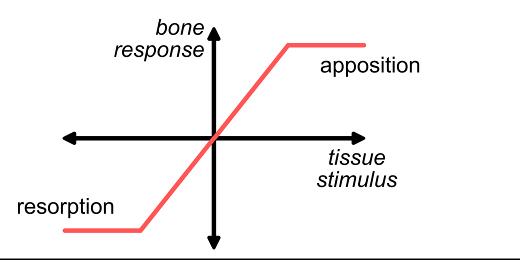
Calculate Tissue-Level Strain Energy Density (SED) from Continuum-Level SED [2]

$$\bar{U}_{\text{tissue}} = U_{\text{cont}}\, \rho^d$$

1) Powerlaw from Homogenization

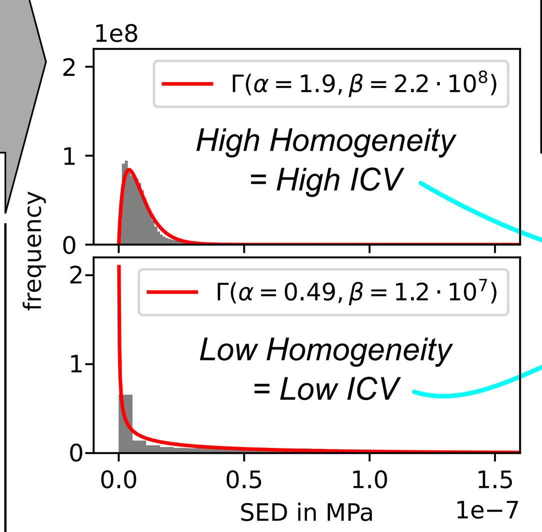


2) Tissue Stimulus from Remodelling Theory



Fit Gamma Distribution to Tissue-Level SED

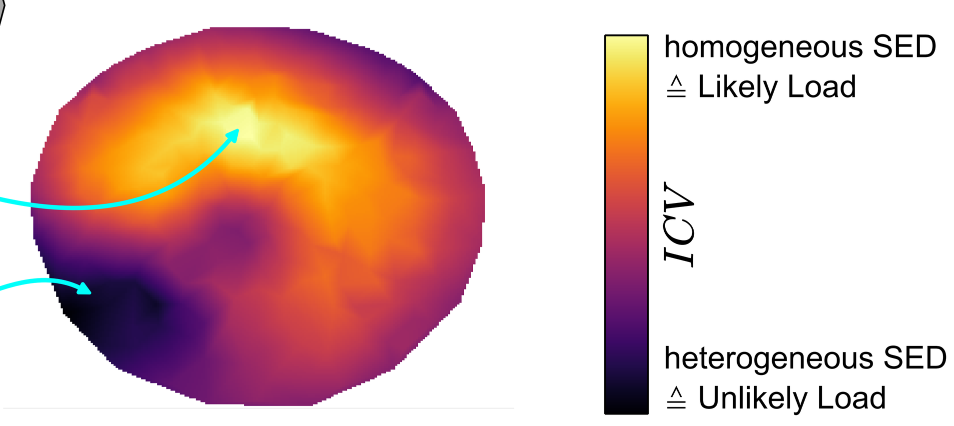
The Gamma Distribution is used to parametrize the SED distribution of each load case.



Calculate Inverse Coefficient of Variation (ICV) from the Fitted Gamma Distribution

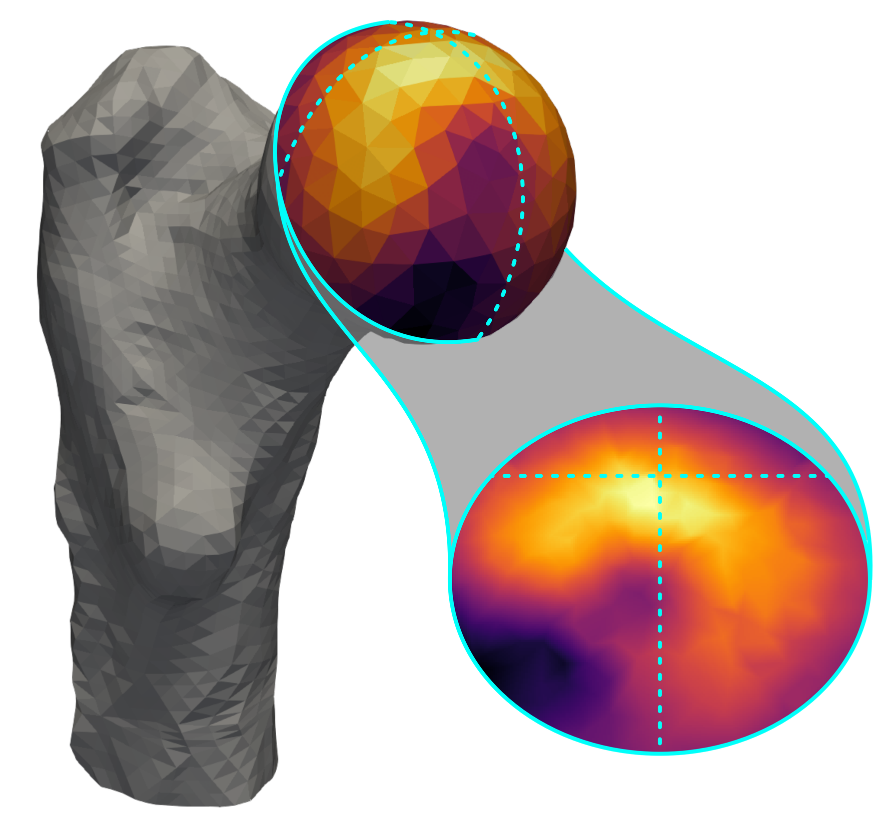
$$ICV = \frac{\mu}{\sigma} = \sqrt{\alpha}$$

Normalize ICV Range per Subject to [0, 1] and Create Load-Case Homogeneity Map

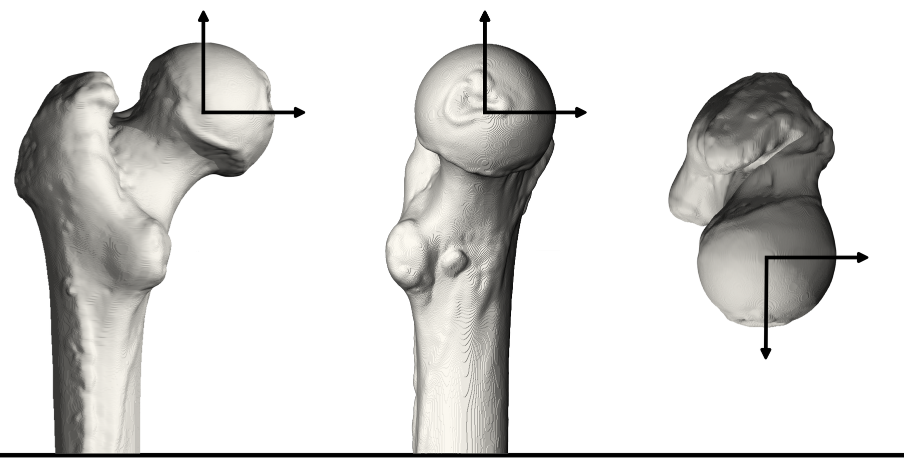


Results

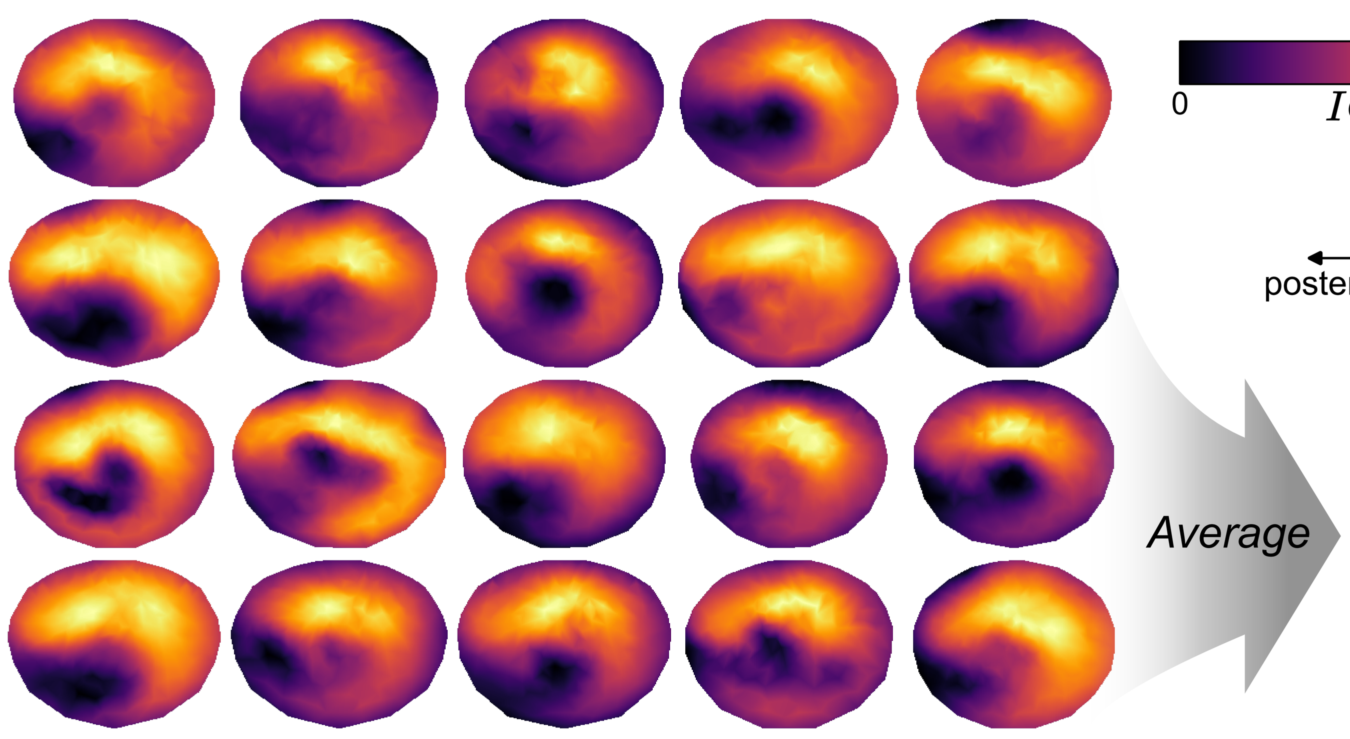
Unwrapping Femoral Head Surface to Map



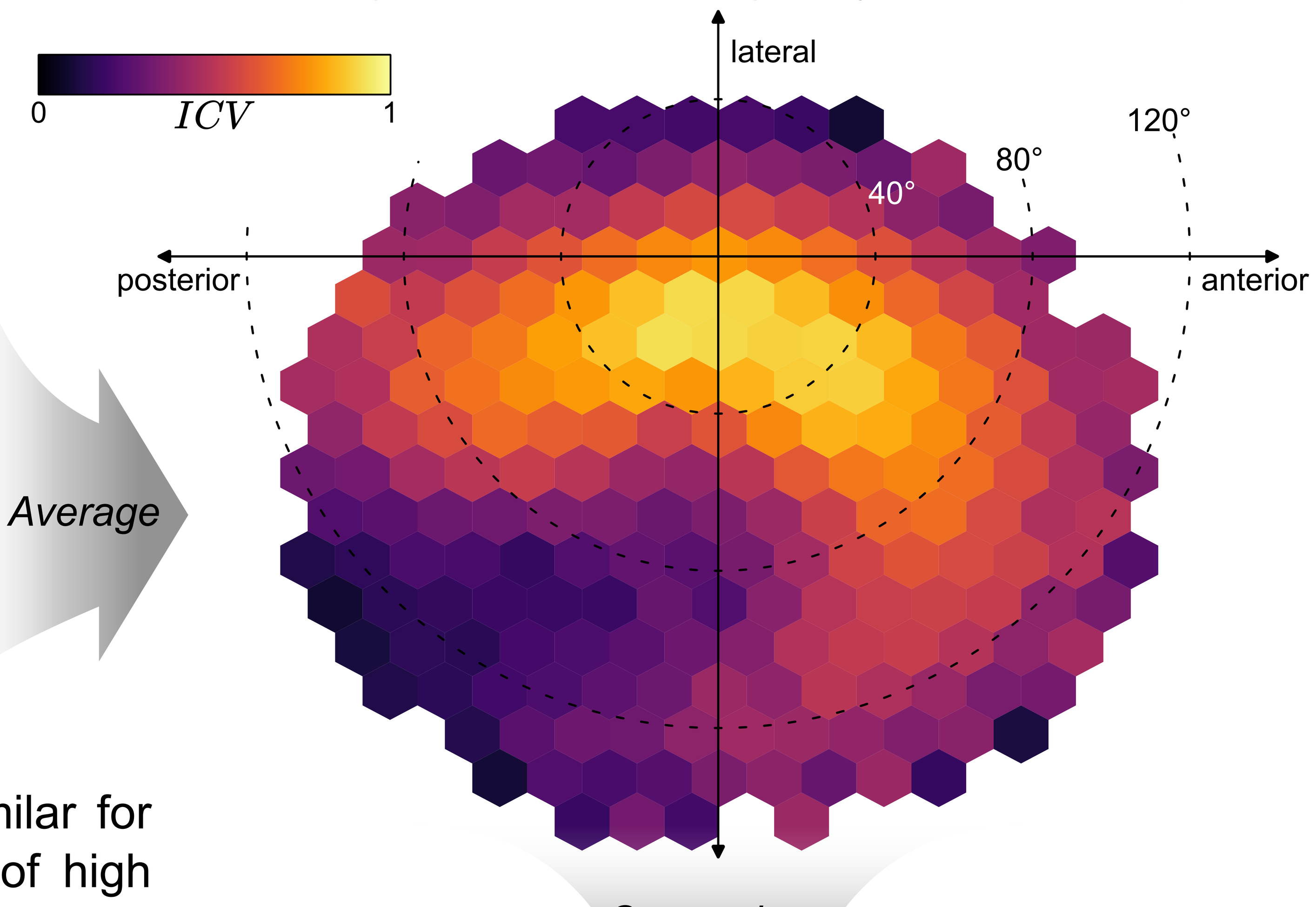
Femoral Head Centered Coordinate System

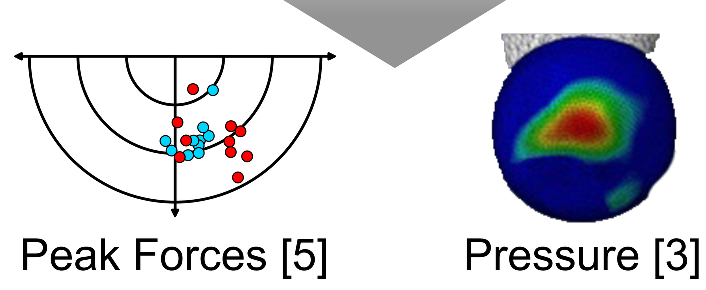


Load-Case Homogeneity Maps for Each Sample



Average Load-Case Homogeneity Map for All Samples





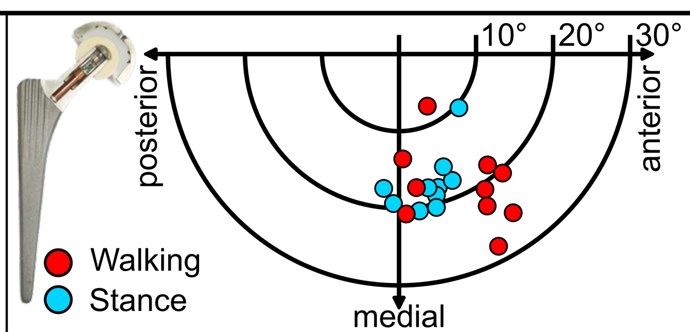
The found load-case homogeneity pattern is similar for all 20 samples and a horseshoe-shaped band of high values is visible in the posterior-anterior direction.
The highest load-case homogeneity is found in the region of approximately 10° to 40° medial.
Low homogeneity is associated with unphysiological loading locations, for example, at the fovea capitis.

Discussion

The same theoretical background of inverse bone remodelling (IBR) was applied with a new evaluation method: Calculating a *load-case homogeneity score* using the inverse coefficient of variation (ICV).

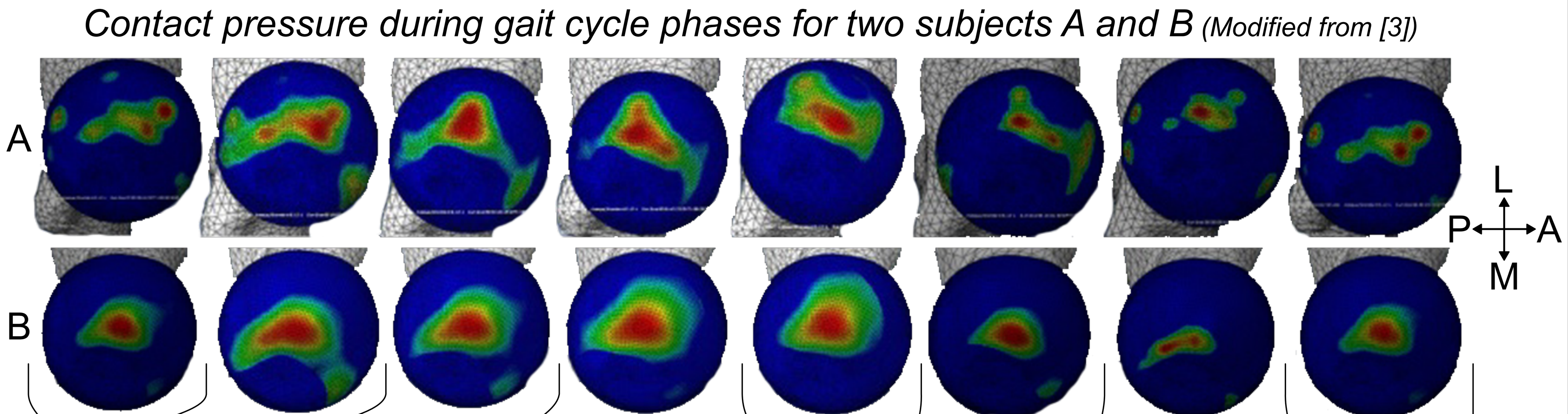
The load-case homogeneity maps show a realistic and physiological distribution, i.e., peak homogeneity is found in the regions of peak forces at the hip [5]. The shape of the distribution qualitatively matches the pressure distributions found during the phases of the highest hip-joint force during walking (phases 2 to 5) [3].
The lowest scores are found in areas of unphysiological loading, such as the fovea capitis and farthest away from the peak loads.
Using a homogeneity score effectively circumvents ambiguous results of inverse bone remodelling when using many test load-cases [4].
The homogeneity score allows the analysis of all applied load-cases separately and can be easily adapted to other boundary conditions, such as contact. However, a limitation of this variation of IBR is that the actual load magnitudes cannot be predicted.

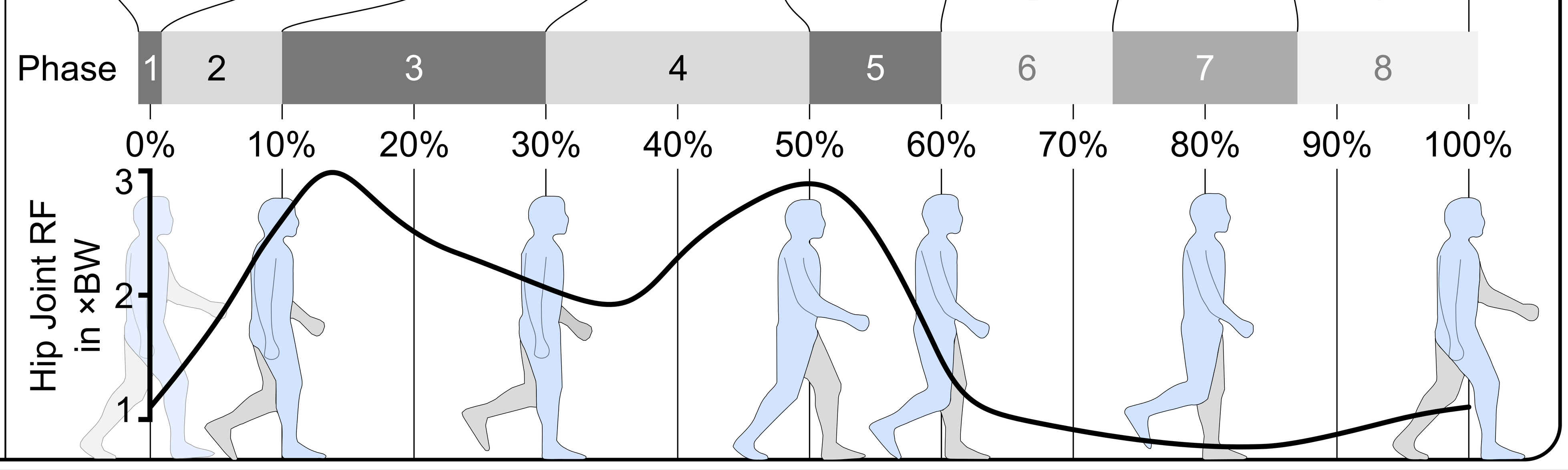
Applying a load-case homogeneity score poses an interesting tool for medical applications. For example, to analyze pathological joint usage or assess fracture risk - by only using CT data.



Position of peak forces at the femoral head, measured with the OrthoLoad system [5]. The peak forces are shown in the same coordinate system as above and for two exemplary load-cases (walking and stance) and 10 patient.

Contact pressure during gait cycle phases for two subjects A and B (Modified from [3])





References

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