A Fast and Biofidelic Repositioning Toolbox for Finite Element Human Body Models

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I. INTRODUCTION

The question of how to rapidly reposition Finite Element Human Body Models (FE-HBMs, e.g., THUMS and GHBMC) with high biofidelity is an important, albeit notorious, problem in vehicle safety and injury biomechanics. The conventional pre-simulation method is extremely time-consuming and leads to element distortion at joints. We propose a fast and biofidelic repositioning toolbox for FE-HBMs. The algorithms are fully geometry-based and simulation-free. It rapidly changes HBM posture based on joint parameters like dummy models. The toolbox will be beneficial to posture-sensitive works, e.g., reclined occupants, pedestrian recognition and personalised protection.

II. METHODS

Geometry-based estimation of arthrokinematics

Dummies can be conveniently repositioned as hinge structure mechanically prescribes the inter-component kinematics. In FE-HBMs, the arthrokinematics is not explicitly given. We propose to estimate subject-specific joint trajectories from the congruent bone geometries. Our algorithm deals with upper and lower limbs. At shoulder and hip, the glenohumeral and acetabulofemoral joints are ball-and-socket type, so the associated arthrokinematics is characterised by 3D rotation about centre of the humerus and femur heads. At elbow, we consider the hinge-type humeroulnar joint. The flexion-extension motion is represented by an in-plane rotation about the estimated centre of the trochlear notch of ulna (Fig. 1(a)). At knee, we extend our previous work [1] on tibiofemoral joint motion prediction and reformulate the computation of flexion axis as optimizing the radii at medial and lateral condyles for best preserving the joint gap distance in between (Fig. 1(b)).

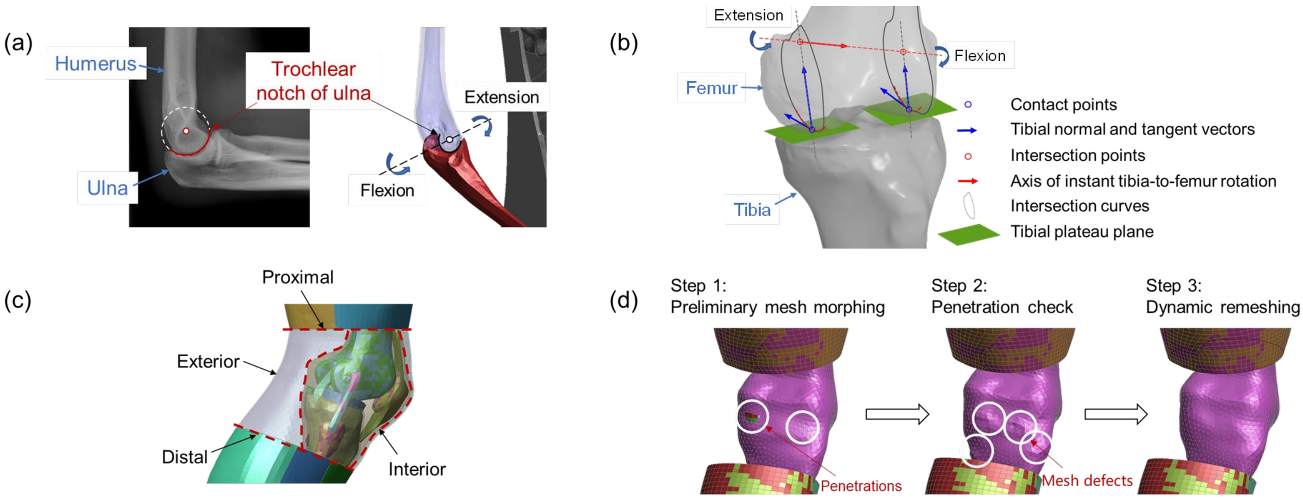

Fig. 1. Geometry-based arthrokinematics estimation at (a) elbow and (b) knee joints; (c) Contour faces of soft tissues; (d) Visualisation of mesh quality in computation of interior face deformation.

Soft-tissue deformation via interpolation

We propose to interpolate soft-tissue deformation based on bone movements. Contour of the tissues is divided into four segments (Fig. 1(c)). The proximal and distal faces are attached to the bones; the interior face slides along the bone-flesh interface; and the exterior face is free. The bone-attached faces rigidly move with the bones. Deforming the interior surface with trivial landmark-based interpolation will overstretch and distort part of the elements as the involved nodes move tangentially with the bone landmarks and get rolled into the

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gap. We propose a hybrid strategy that combines mesh morphing, penetration check and dynamic remeshing (Fig. 1(d)), which jointly satisfies the geometric constraints and preserves mesh quality. The remaining nodes (transparent in Fig. 1(c)) including the exterior face and inside are interpolated via thin-plate spline, according to the landmarks (red dashed lines in Fig. 1(c)) before and after bone movements.

The Fast and Biofidelic Repositioning Toolbox

The toolbox takes joint parameters as input, i.e., 3×3 rotation matrices for shoulder and hip joints and scalar 1D angles for elbow and knee joints, on the left and right sides. Centres of humerus head, trochlear notch of ulna and femur head, as well as the trajectory of knee flexion are precomputed based on model geometry. The codes are jointly implemented in MATLAB and with PyTorch3D [2] in Python.

III. INITIAL FINDINGS

We apply the proposed toolbox to THUMS occupant and pedestrian models (AM50, v4.1/4.0.2). The occupant model is repositioned to a highly reclined pose and an arbitrary driving posture, respectively (Fig. 2(a)). Details at the knee joint during the normal to reclined posture change are illustrated in Fig. 2(b). Our method successfully preserves the gap distance at knee. The connective tissues (e.g., ligaments) and fleshes are deformed accordingly. When repositioning the pedestrian model, we exploit a computer vision model, Expose [3], to recognize pedestrian poses from image, and use the inferred joint parameters as input, as shown in Fig. 2(c) and (d). Inference with Expose takes 20 seconds and the toolbox takes about 3 minutes on a desktop PC with Intel 10700 CPU and Nvidia RTX 3070 Ti GPU. The entire pipeline is fully automatic, and the generated model is ready-to-use with comparable mesh quality to the baselines without any post-processing.

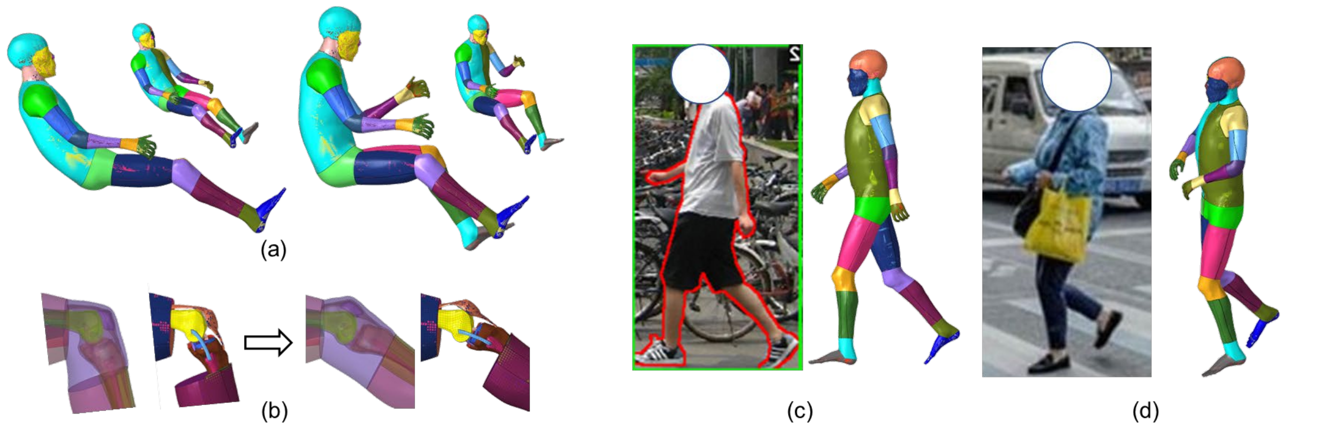

Figure 2. Demonstration of repositioning THUMS occupant (a, b) and pedestrian (c, d) models with the toolbox.

IV. DISCUSSION

Our toolbox is 'dummy-like', as dummies can be easily repositioned with given angles at joints. Compared to existing methods, our method supports estimation of subject-specific arthrokinematics, especially at the knee joint, and provides accurate control of soft-tissue deformation, even in highly flexed or extended cases (Fig. 2). The toolbox is biofidelic, automatic, robust and time-efficient. It can benefit all posture-related tasks.

Due to the complexity of knee anatomy, the geometry-compatible motion space is actually 2-dimensional. We present a 'neutral' solution in Fig. 2(b), where the contact point stays stationary on the tibia plateau. Identifying the exact path relies on kinetic analysis, which requires external loads and tissue properties. The current algorithms cannot preserve mass or volume in computation. In future, the exterior face deformation can be controlled by physics-informed skinning techniques to further improve biofidelity. Now our toolbox considers only the limbs, but in future the spine, wrists, ankles and other joints will be incorporated.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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