# A generic Positioning Tool for Human Body FE Models

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***Abstract*** Human body finite element (FE) models are used in pedestrian protection and occupant safety simulations. These human models are normally only available in standard occupant and pedestrian postures. These postures may not be adequate for all crash scenarios, and this limits the usability of human body models FE in the future. Due to detailed modeling of skin, flesh and ligaments in the human FE model, the positioning technique of human body is entirely different and much more complex than that of dummy models and current methods do not offer easy and quick positioning of human models. This paper focuses on the development of a general-purpose positioning tool as well as the use of kinesiology to achieve anatomically correct postures of the human model. The positioning requires a mesh smoothing step which is realized using a local dual kriging approach. Scientific knowledge of joint kinematics is essential to achieve anatomically correct postures which are obtained from kinesiology. The findings of kinesiology are incorporated into the positioning tool to reduce the user dependency in achieving anatomically correct postures. The tool facilitates the generation of anatomically correct postures quickly. This paper describes the positioning method in more detail and gives some practical examples of posture change.

***Keywords*** human body FE model, joint kinematics, kinesiology, kriging, positioning tool

## I. INTRODUCTION

In pedestrian protection and occupant safety simulations, dummy models are widely used to evaluate human safety. On the other hand, the use of advanced computing technology has facilitated many detailed studies on the modeling of the human body using numerical methods. Several human body models have been developed using the finite element (FE) method [1]-[2]-[3]. Usually, the human FE model contains detailed modeling of bones surrounded by soft tissues like skin, flesh and ligaments. One of these models is the *Total Human Model for Safety* (THUMS), which is jointly developed by Toyota Motor Corporation and Toyota Central R & D Labs., Inc. The THUMS is available in standard pedestrian and occupant postures only. Pedestrian models are in walking posture with fixed arm and leg angles and occupant models are in driving posture in a very upright position. These current postures may limit their usability in future applications. Depending on the vehicle model, the seating side (driver, co-driver) or the required step posture, different model positions have to be considered. This gives emphasis to standardized model positioning approach. The model positioning generally requires mesh transformation techniques, mainly translation and rotation. As per requirement dummy models are very easy to position in a rather short time using existing FE pre-processors, mainly due to their simple modeling technique. In the case of human FE models, soft tissues get deformed during the actual movement which is difficult to capture using existing FE preprocessors. Here, one needs to divide the whole positioning process into a number of small steps. Additionally, the positioning region has to be modified in each step. Each small step results in penetrations among the elements, element distortion and negative volumes in the elements which then need to be corrected manually. This activity takes a lot of time and especially if the positioning process is repetitive in nature, it is difficult to do. The problem dealt with in this paper is typical for FE human body models. In multi-body human models this problem often can be avoided by a proper choice of the model in general and the joint rotations in particular.

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Reference [4] focused on dynamic simulations for positioning the human FE model. It was observed that the process is time consuming and the final posture may contain distorted elements which require a manual mesh correction. Additionally, the anatomical correctness of the final position and the kinematics as a result from the dynamic simulation are uncertain.

Reference [5] reported a methodology on repositioning human body FE models. Bones were repositioned using transformations and the soft tissues were mapped onto the bones in their new position using a Delaunay triangulation based mapping. The methodology was demonstrated by repositioning the knee joint only. Therefore, the knee joint kinematics was studied in detail to produce an anatomically correct posture.

To achieve an anatomically correct posture, the knowledge of joint kinematics is essential. Furthermore, to cover all versatilities of crash scenarios, joint kinematics of major human body joints needs to be considered. Such information is widely available in the science of human kinetics known as *kinesiology*. Kinesiology is a combination of *kinesis* (Greek: move) and *ology* (Greek: study). Thus kinesiology is the scientific study of human movement [6]-[7]. It brings together the field of anatomy, physiology, physics and geometry and relates them to human joint movements. Kinesiology gives the knowledge of motions of a particular joint allowed anatomically and the locations of the rotation axis for each motion [7]. Kinesiology is widely used in physical and occupational therapy.

This paper describes the development of a general-purpose positioning tool to automatically perform the required positioning tasks. A mesh smoothing step is developed to account for smooth mesh geometries between translating and rotating parts to ensure a decent mesh quality after the positioning process for the final body posture. This step is realized using a local dual kriging approach, which represents a geo-statistical method to interpolate nodal coordinates, based on the motion of a set of control points. This paper additionally addresses the use of kinesiology to get anatomically correct human posture. Finally, some examples have been demonstrated of practical applications of adaptation of the human FE model to different step postures.

## II. METHODS

### *The Positioning Tool Approach*

The methodology for the positioning process is based on the positioning approach used for conventional dummy models. Here, a rigid body chain of the dummy is created using so-called tree files, where the model is divided into rigid regions, connected by joints. The model can then be repositioned by simply changing the joint angles. As a result of the positioning requirements of the corresponding hardware dummies, the fundamental advantage of the dummies is that the joints (e.g. elbow, knee or hip) are usually not covered by any materials, which can deform during the positioning process (Fig. 1). Therefore, this process reduces to a pure rigid body motion (mainly rotation).

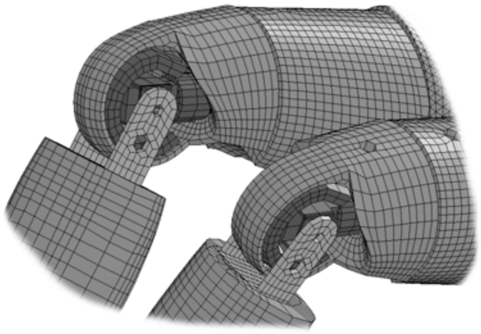

Fig. 1. “Knee” detail of the THOR dummy modeled as hinge

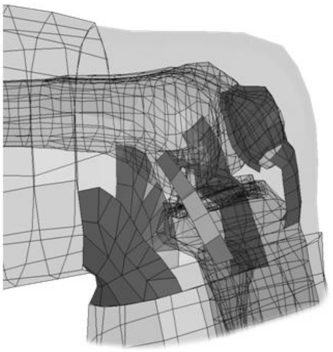

Fig. 2. “Knee” detail of the THUMS model with covering flesh, ligaments and hollow of the knee

However, the structure of human models is very different. Joints are modeled more realistically and the joint degrees-of-freedom are governed by contact conditions between the joint bones and supporting ligaments (Fig. 2). Additionally, the joints are covered by shell or solid elements, representing soft tissues like flesh, muscles, fat or skin layers. Therefore, repositioning of human models is usually not a simple rigid body positioning, but rather a complex model and mesh modification process, including mesh smoothing in the transitional regions and preventing self-penetrations of the joint parts.

***Positioning Methodologies*** A very straight-forward approach is the positioning using finite element simulations, where adequate boundary conditions are used to move specific body regions into their final position. Any transitional parts are deformed accordingly. This approach accounts for the physical behavior of the materials and prevents self-penetrations due to defined contact conditions within the joint region. However, a fundamental problem with this approach is that the mesh quality after the positioning might be very bad due to local oscillations in a dynamic simulation. Therefore a manual mesh smoothing is required which is usually very time-consuming.

To reduce the model oscillations, a *hybrid approach* can also be used, which combines the advantages of the standard dummy positioning and the positioning via FE simulations. First, a rigid body chain is created from the original human model, where regions that do not deform during the positioning process are combined to rigid bodies. These rigid bodies are connected using rigid body joints, e.g. hinges, translational or spherical joints. Parts that will deform during the positioning process (flesh, skin and ligaments in the transitional joint regions) are left deformable, such that the model deformations are restricted to these deformable parts, reducing the simulation time. Although, the model regions that potentially have to be smoothed manually are minimized, this approach might still lead to local oscillations within the deformable parts and thus additional mesh correction work.

***Methodology of the Positioning Tool*** The positioning approach applied here is similar to the hybrid approach, as described above. However, instead of finite-element simulations, a geometric smoothing process is chosen to circumvent the above mentioned problems. The user defines rigid and deformable model regions, along with the actual positioning commands. These positioning commands might include mesh transformations like rotations, translations or a scaling of the whole model or single model regions. Since a geometric transformation of single parts within a model will most likely lead to local deformations within adjacent parts (Fig. 3b), a smoothing procedure is necessary to adapt the mesh of these adjacent or transitional parts (Fig. 3c).

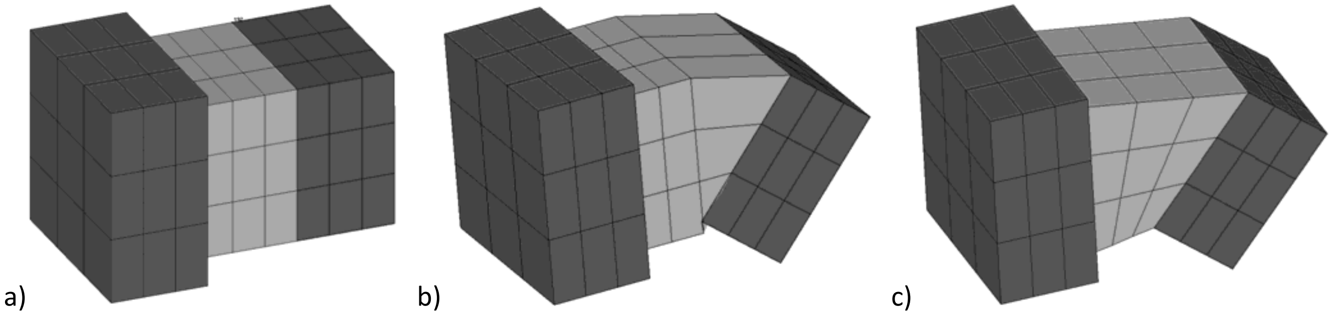

Fig. 3. Simple test system (a), geometric rotation of the right part leads to locally deformed elements (b); including a local kriging process leads to regular deformed elements in the adjacent part

Such a mesh smoothing procedure can be obtained using a local dual kriging approach. As a geostatistical technique, kriging can be used as a control-point based mesh smoothing procedure, interpolating the nodal displacements ***u(x)*** at arbitrary locations ***x*** from values $\bar{\boldsymbol{u}}(\boldsymbol{x}_i)$ at given control point locations $\boldsymbol{x}_i$. Control points in this sense are points, where the location is known before and after the geometric transformation. This includes nodes on parts that are not positioned ($\bar{\boldsymbol{u}}=\boldsymbol{0}$) or nodes that are transformed using a specific transformation command ($\bar{\boldsymbol{u}}\neq\boldsymbol{0}$). The motion of the control points governs the displacement of the nodes in the transitional region. The kriging method performs a *least-squares* estimation, where the unknown nodal displacements are given as a linear combination of the *N* known values (control points) $\bar{\boldsymbol{u}}(\boldsymbol{x}_i)$ using the weights $\omega_i(x)$

$$u^n(x) = \sum_{i=1}^{N} \omega_i(x) \cdot \bar{u}(x_i). \tag{1}$$

The weights $\omega_i(x)$ are computed following the dual kriging approach which finally leads to a minimization problem and the solution of an *MxM* equation system, where *M=3N+3* and *N* being the number of control points each with 3 coordinates in space. This approach is described in more detail in [8]-[9].

Crucial for the performance of the kriging method is a proper definition of the control points, which basically represent the connected nodes from the parts to be smoothed. These nodes can either be directly connected nodes or nodes connected by contact or rigid body connections. The initial and deformed position of these nodes is known from the rigid body positioning step and can thus be used as control points.

The positioning tool takes care of mesh flow of the deformable parts during the movement. But the obtained final posture must be anatomically correct. To get anatomically correct posture the joint kinematics knowledge is referred from the *kinesiology.*

***Kinesiology***

The kinesiologies of major human joints are studied. The relative motion between two connected segments in the human body can be described by 6 degrees of freedom. Due to joint contact surfaces, ligaments, capsule etc. the actual number of degrees of freedom is often less. In many joints it is acceptable to focus only on relative rotations (max. of 3 degrees of freedom) because relative translations can be neglected. Neglecting translation motion in the joint causes negligible error. Therefore in this paper we only focus on relative rotations. So the accuracy of the repositioning is depending on right selection of rotation axis. The information on possible motions at major human body joints and the corresponding rotation axis is present in the APPENDIX. Based on the information, rotation axes were determined in the joints in human body FE model.

In the shoulder, complex motion occurs at four distinct articulations and makes the movement complex with no fixed center of rotation [6]-[10]-[11]. This complexity was the reason for the simplification, where only the glenohumeral joint in shoulder kinematics is considered. Therefore, three mutually perpendicular rotational axes passing through the geometric center of the humeral head were determined within the shoulder joint of the human FE model (Fig. 4). Humerus movement induces scapula movement [6]-[7]-[12], but for simplification, it is assumed that the scapula is motionless throughout the shoulder movements.

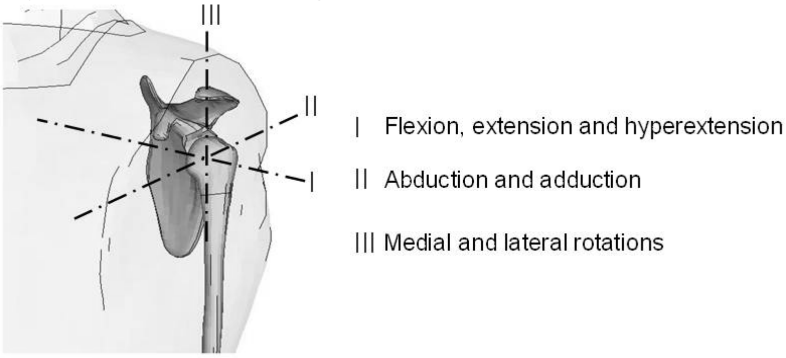

Fig. 4. Three mutually perpendicular rotational axes passing through geometric center of the humeral head of human FE model

The coupled axial rotation of elbow joint is ignored as its value is very small [17]. The trochlear sulcus and capitellum are not present in the human model so the flexion and extension axis of elbow joint was approximately determined in the humerus of the human FE model as shown in Fig. 5. Figure 6 is showing the pronation and supination axis of forearm passing through the center of the radial head and the distal ulnar head of the human FE model. Wrist joint rotation axes, passing through the center of the capitate were determined to perform the hand movements.

Fig. 5. Flexion-extension axis of the left elbow of human FE model

Fig. 6. Pronation and supination axis of the forearm of human FE model

The axes passing through the geometric center of the femoral head were determined in the hip joint of the human FE model as shown in Figure 7. In knee joint, coupled motion is present between flexion-extension and axial rotation. Apart from this coupled motion, knee flexion introduces additional degree of freedom (independent axial rotation) in the knee joint. So the knee axial rotation is possible either in coupled or in independent way. Here, the coupled axial rotation during knee flexion is ignored and considered only the independent axial rotation. One can achieve the coupled motion by considering it as a two separate motions. But one must know the relation between flexion-extension and axial rotation. The knee flexion-extension axis is approximated by a fixed axis passing through the center of the medial and lateral epicondyles of the femur and the internal-external rotation axis is approximated by an axis passed through the mid-point of the medial spine of the tibial eminence as shown in Figure 8. The patella flexion axis is approximately located on the femoral condyles.

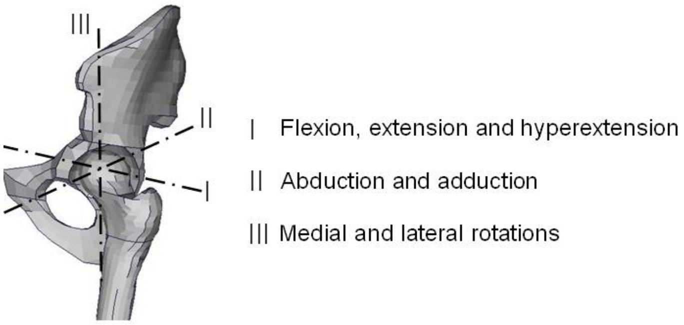

Fig. 7. Three mutually perpendicular rotational axes passing through geometric center of the femoral head of human FE model

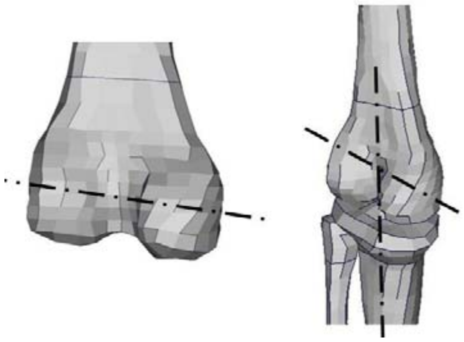

Fig. 8. Flexion-extension and internal external rotation axis of the left knee

The axis of talocrural joint and talocalcaneal joint of the wrist joint was located in the human FE model (Fig. 9 and Fig. 10). The flexion-extension and axial rotation axes were located in the cervical spine of the human FE model (Fig. 11). The occipital is not present in the model so it is assumed that articulation takes place between head and atlas.

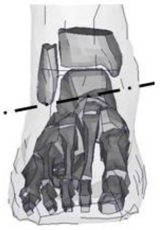

Fig. 9. Axis of dorsiflexion and plantarflexion in human FE model

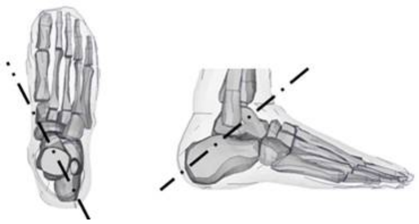

Fig. 10. Axis of inversion and eversion in human FE model

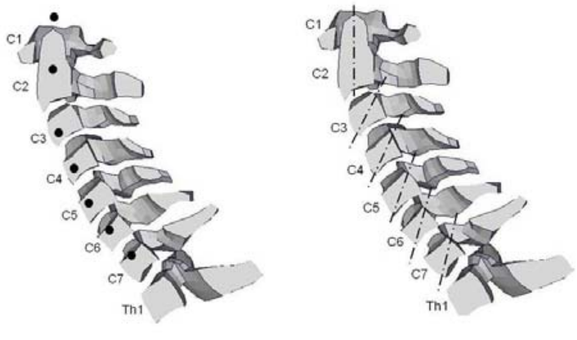

Fig. 11. Flexion-extension and axial rotation axes in human FE model

The definition of the rotation axis, deformable and undeformable parts of every movement is incorporated in the tool. This will eliminate multiple inputs required from the user and ensure error proofing. The process requires only a rotation angle as user input. The accuracy and performance of the tool is demonstrated by performing movements at the major joints. The knee positioning was finally checked for mesh quality parameters.

## III. RESULTS

The tool is capable of creating smooth geometric transitions between the parts during the repositioning process. Soft tissues like skin, flesh and ligaments in the joint region were deformed in a realistic manner. It repositions the model in less time compared to conventional positioning methods. The incorporation of kinesiology knowledge supports the accuracy of the anatomy of the repositioned model. The positioning process does not generate any kind of strain or force in the repositioned model. Using this tool, we are able to generate anatomically correct postures with only one (rotational angle) user parameter. Some of the generated movements are shown in Figure 12 to Figure 19.

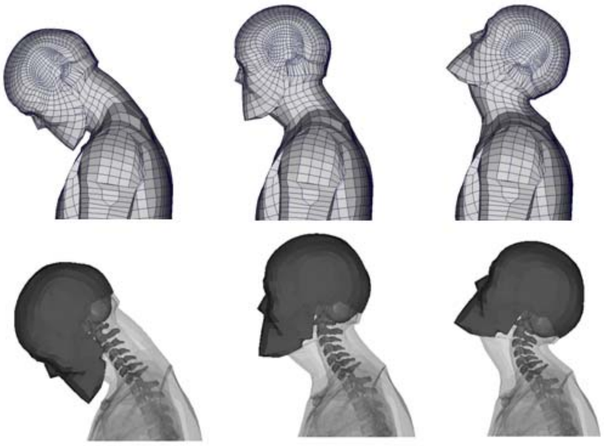

Fig. 12. Head flexion and extension

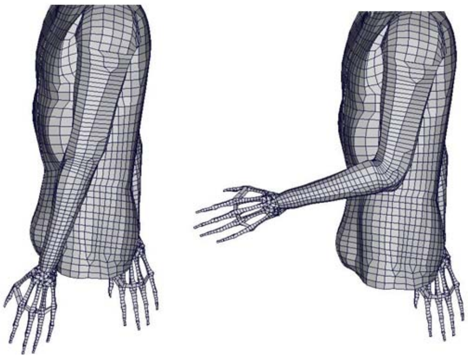

Fig. 13. Elbow flexion

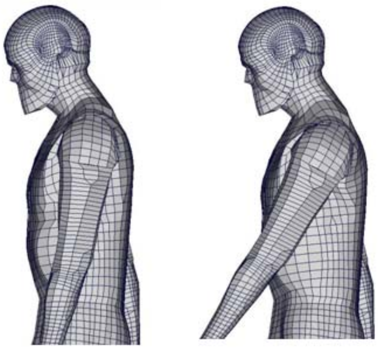

Fig. 14. Shoulder flexion

Fig. 15. Ankle dorsiflexion and plantarflexion

Fig. 16. Ankle inversion and eversion

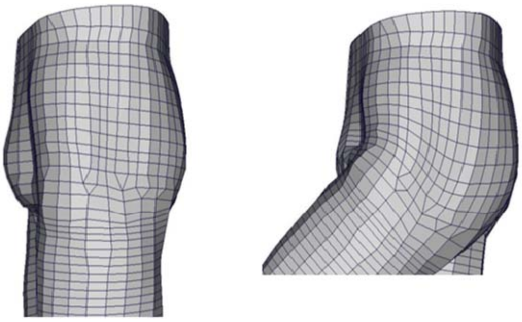

Fig. 17. Hip joint flexion

Fig. 18. Hip joint abaduction and adduction

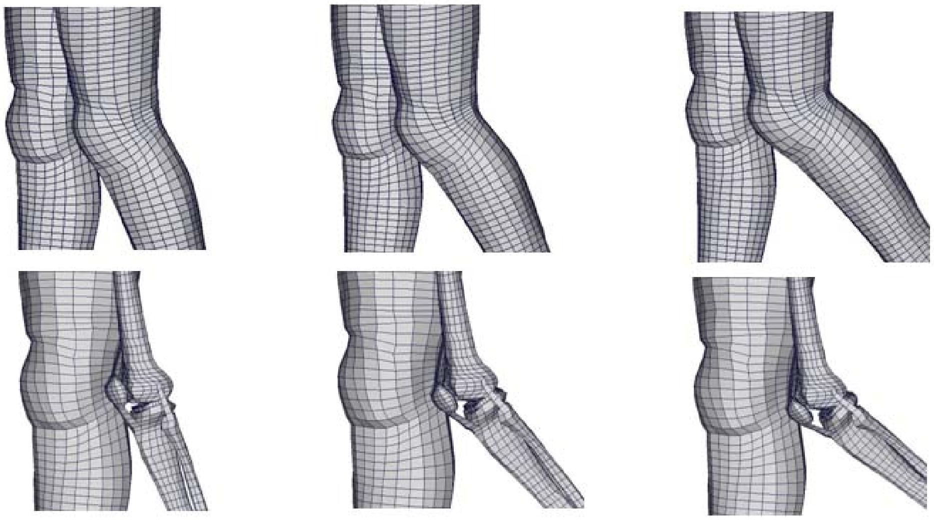

Fig. 19. Knee flexion

The mesh quality has been checked during the knee flexion. The mesh quality parameters have been given in Table I. The quality parameters are slightly affected till $40^0$ knee flexion except warpage and aspect ratio.

TABLE I

MESH QUALITY CHECK

| Knee flexion angle (deg) | Warpage (Max) | Aspect ratio (Max) | Jacobian (Min) | Time (ms) (Min) | Skew (Max) |
|---|---|---|---|---|---|
| 0 | 52.61 | 6.8 | 0.38 | 5.41E-4 | 48.60 |
| 10 | 52.83 | 6.58 | 0.37 | 5.41E-4 | 45.54 |
| 20 | 53.34 | 6.36 | 0.35 | 5.41E-4 | 49.22 |
| 30 | 64.97 | 7.05 | 0.32 | 5.41E-4 | 54.61 |
| 40 | 85.52 | 11.06 | 0.30 | 5.41E-4 | 59.60 |

## IV. DISCUSSION

A positioning methodology, based on a dual kriging approach, allows deformations within the soft tissues during the positioning process. Additionally, kinesiology of seven major joints was studied to locate the axes of motion. Obtained kinesiology knowledge was incorporated into the tool to reduce user dependency in achieving anatomically correct postures. The achieved movements are within anatomical limits and look realistic. The repositioned model does not require any re-meshing and can directly be used for further applications. The tool repositions the human model with ease and is generally not limited for use with the THUMS model rather it can be used for all kinds of FE models. The applicability of the tool was demonstrated by performing movements at several joints and it is also possible to perform several movements simultaneously.

However, the accuracy of the rotation axis depends on the geometric details of the bones. At present, the location of the rotational axes cannot be altered during the movements as it is for instance required in knee flexion-extension. Another limitation is that the mesh connectivity remains constant during the positioning process and only the mesh nodes are relocated in space. Therefore, the model positioning is limited to small to moderate posture changes, depending on the rotation angle and the resulting element distortions. In some cases at large rotation angles, the element quality and thus the model stability might deteriorate considerably.

## V. CONCLUSIONS

A positioning tool with incorporated kinesiology gives anatomically correct postures within a few seconds with less user involvement. The repositioned model does not require any subsequent manual re-meshing and can directly be used for further applications. The tool is very useful for accident reconstruction, Out Of Position (OOP) applications or other applications in which the human body model FE technology may be used.

The positioning accuracy can be further improved by

- improving the kriging method for large scale meshes,
- detailed capturing of articulating surfaces geometry in human FE model,
- introducing instant axis of rotation in the positioning tool.

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## VII. APPENDIX

***Kinesiology of the Shoulder Joint*** The shoulder complex represents the group of structures connecting the arm to the thorax. The combined movements of four distinct articulations – glenohumeral (shoulder), acromioclavicular, sternoclavicular, and scapulothoracic joints allow the arm to be positioned in space [11]. Among these joints, the glenohumeral is the most mobile joint. The center of rotation of the glenohumeral joint has been defined as a locus of points situated within 6.0 ± 1.8 mm of the geometric center of the humeral head [11]. The shoulder joint is a ball and socket joint and has three degree of freedom. There are four groups of motions possible at the shoulder joint. Flexion, extension and hyperextension occur in the sagittal plane around the frontal axis. Abduction and adduction occur in the frontal plane around the sagittal axis. Medial and lateral rotations and also horizontal abduction and horizontal adduction occur in the transverse plane around the vertical axis.

***Kinesiology of the Elbow Joint*** The articulation of the humerus with the ulna and radius is commonly called the elbow joint. The elbow joint allows flexion and extension coupled with an axial rotation. On the humerus, the trochlea articulates with the trochlear notch of the ulna and the capitulum articulates with the head of the radius. There is no hyperextension at the elbow [7]. The elbow flexion and extension axis can be approximated by a line passing through the centers of the trochlear sulcus and capitellum (Fig. 20) [12]-[13]-[14]-[17]. The instant centers of flexion and extension vary within 2–3 mm of this axis [11].

The radioulnar joint is a uniaxial pivot joint. At the proximal end, the head of the radius pivots within the radial notch of the ulna and at the distal end, the ulnar notch of the radius rotates around the head of the ulna. It allows only pronation and supination of the forearm. When pronation and supination occur, the radius moves around the ulna. The ulna does not rotate. It is locked in place by its bony shape at the proximal end [7]-[16]. The centre of rotation lies very close to a line extending from the centre of the radial head to the centre of the ulnar head (Fig. 21), however instant rotational centers are distributed over a small range [15]-[6]-[12]-[17].

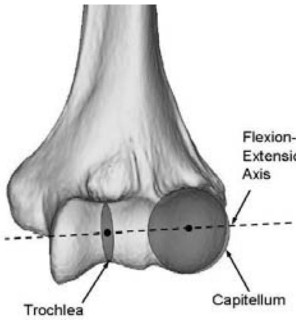

Fig. 20. Flexion-extension axis of the left elbow [14]

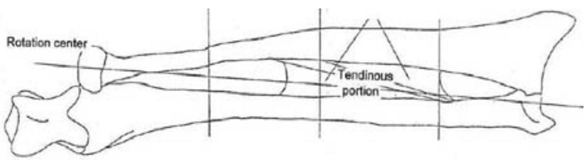

Fig. 21. Pronation and supination axis of the forearm [15]

***Kinesiology of the Wrist Joint*** The wrist functions by allowing changes of orientation of the hand relative to the forearm. The wrist joint is actually made up of the radiocarpal joint and the midcarpal joint. The radiocarpal joint allows flexion and extension, plus radial deviation and ulnar deviation. The complexity of joint motion at the wrist makes it difficult to calculate the instant center of motion. However, the trajectories of the hand during radioulnar deviation and flexion/extension, when they occur in a fixed plane, are circular and the rotation in each plane takes place about a fixed axis. These axes are located within the head of the capitate and are not altered by the position of the hand in the plane of rotation [11]. Flexion and extension occur around the frontal axis passing through the center of the capitate. Radial and ulnar deviations occur around a line perpendicular to the plane of the palm passing through the intersection of the capitate and lunate [6]-[12].

***Kinesiology of the Hip Joint*** The hip joint is composed of the head of the femur and the acetabulum of the pelvis. It is a ball-and-socket joint and possesses three degrees of freedom of motion. All movements take place about three mutually perpendicular axes that intersect at the geometric center of the spherical femoral head [6]. The transverse axis lies in the frontal plane and controls movements of flexion and extension. An anterior/posterior axis lies in the sagittal plane and controls movements of adduction and abduction. A vertical axis which coincides with the long axis of the limb when the hip joint is in the neutral position controls movements of internal and external rotation. Surface motion in the hip joint can be considered as spinning of the femoral head on the acetabulum.

***Kinesiology of the Knee Joint*** The knee is the intermediate joint of the lower limb. It is composed of the distal femur and proximal tibia. The knee joint is composed of the tibiofemoral articulation and the patellofemoral articulation. The tibiofemoral joint is mainly a joint with two degrees of freedom. The first degree of freedom allows flexion and extension. The second degree of freedom is the axial rotation around the long axis of the tibia. Rotation of the leg around its long axis can only be performed with the knee flexed. There is also an automatic axial rotation which is involuntarily linked to flexion and extension. When the knee is flexed, the tibia internally rotates and when the knee is extended, the tibia externally rotates. The flexion/extension axis is defined differently by many researchers. Some studies mentioned that flexion-extension occurs around an instantaneous axis [5]-[6]-[18]-[19]. Reference [20] assumed that a fixed axis of rotation is coincident with the centers of the posterior femoral condyles. Similarly, reference [21] found an optimal axis of flexion/extension which passes from a point on the medial femoral condyle posteriorly and proximally to the lateral condyle (Fig. 22). The work of [22] showed that the centres of the condylar circles are very close to a line through the epicondyles thus providing anatomical landmarks for locating the axis of flexion/extension. Reference [24] determined the flexion/extension axis of the knee joint as fixed and passing through the origins of the medial and lateral collateral ligaments and superior to the crossing point of the cruciates. The internal/external rotation axis passes through the mid-point of the medial spine of the tibial eminence [24]-[25]. Reference [26] stated that internal/external tibial rotation occurred about the medial part of the tibia. Reference [23] suggested that the internal/external rotation axis passes through the tibial insertion of the anterior cruciate ligament. During knee flexion, the patella makes a rolling/gliding motion along the femoral articulating surface. In this study only the patella gliding has been considered. As the knee flexed the patella flexed by 0.66 times the tibiofemoral flexion angle [27].

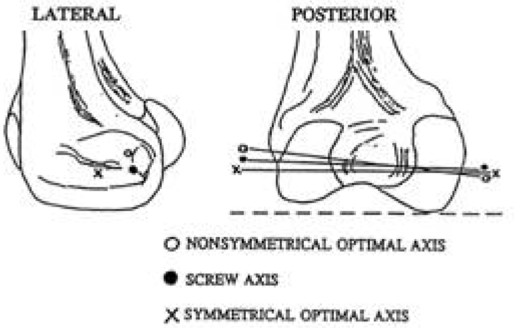

Fig. 22. Flexion-extension axis
of the left knee [21]

***Kinesiology of the Ankle Joint*** The ankle joint is composed of two joints, the talocrural (true ankle) joint and the talocalcaneal (subtalar) joint (Fig. 23). The talocrural joint is formed by the articulation of the distal tibia and fibula with the trochlea of the talus. The motion that occurs in the true ankle joint consists of dorsiflexion and plantarflexion. The axis of motion passes through the inferior tibia at the fibular and tibial malleoli [6]-[11]-[28]-[29] as shown in Figure 24. The talocalcaneal joint is formed by the articulation of the talus with the calcaneus. The motion that occurs in the talocalcaneal joint consists of inversion and eversion. The axis of motion passes from the anterior medial superior aspect of the navicular bone to the posterior lateral inferior aspect of the calcaneus [6]-[11]-[28]-[29] as shown in Figure 25.

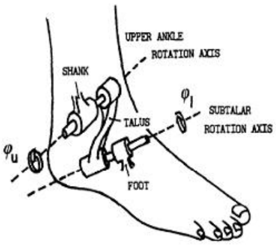

Fig. 23. Kinematic model
of human ankle [28]

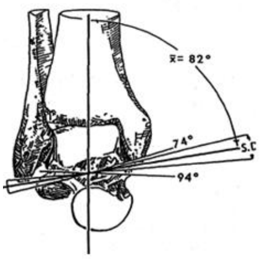

Fig. 24. Axis of dorsiflexion
and plantarflexion [11]

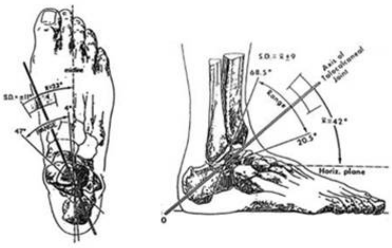

Fig. 25. Axis of inversion
and eversion [11]

***Kinesiology of the Neck Joint*** The neck comprises the region between the thoracic and the base of head. Kinematically the neck consists of eight joints of complex geometry known as a cervical spine. It allows flexion and extension, lateral bending and axial rotation. In this study, only the flexion-extension and axial rotation of the head are considered. The cervical spine consists of seven vertebrae C1 to C7. The articulation between the occipit and C1 (atlas) forms the atlanto-occipital joint. The only movement possible at this joint is flexion and extension. The axis of flexion and extension is located above the atlas as shown in Figure 26. During flexion and extension, the first rotation is performed at this joint and then the lower spine becomes involved [33]. Axial rotation and lateral flexion are not physiological movements of this joint [31]-[32]. The articulation between the C1 and C2 forms the atlanto-axial joint. The major movement at this joint is axial rotation. The axis of rotation is shown in Figure 27. About 50% of neck axial rotation takes place at this joint. The first $45^0$ of rotation occurs at C1-C2 and then the lower spine becomes involved. The motion in each plane is equally distributed from C3 to C7 through motion segments [33]. The typical cervical segments (C3-C7) exhibit flexion/extension, lateral flexion and axial rotation about the certain rotational axis (Fig. 28). The upper vertebra moves over the lower vertebra and the motion get transferred from upper region to lower region of the cervical spine. Since the facets are orientated at about 45° to the transverse plane of the vertebrae, the axis of rotation is 45° from the conventional axes of both horizontal axial rotation and lateral flexion. The mean location of instantaneous axis of rotation in flexion and extension at each segment [31]-[34]-[35]-[36] is shown in Figure 29.

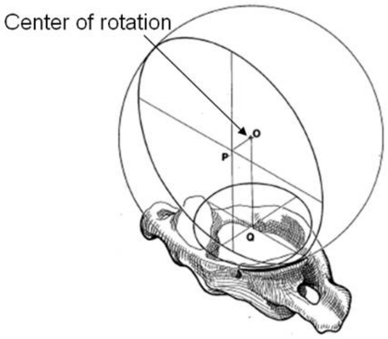

Fig. 26. Center of rotation of atlanto-occipital joint [30]

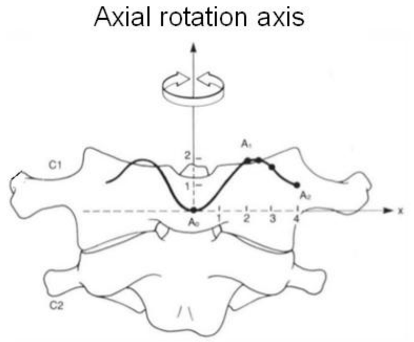

Fig. 27. Axial rotation axis of atlanto-axial joint [35]

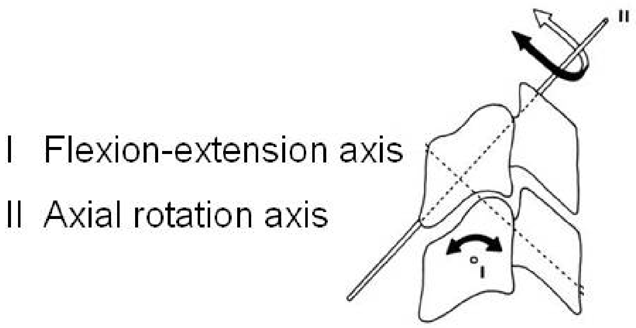

Fig. 28. Axes of motions of typical cervical segment [31]

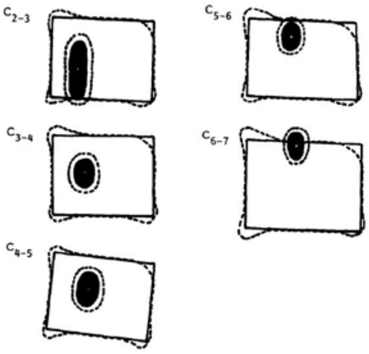

Fig. 29. The distribution of flexion-extension axis of rotation in cervical segments [36]