Modeling Skin Deformation Using Boundary Element Method

Y. M. Tang

The Hong Kong Polytechnic University, mfymtang@inet.polyu.edu.hk

ABSTRACT

Modeling human skin deformation has many applications in the areas of computer graphics and human biomechanics. Nevertheless, most of the existing deformation approaches are too simple to be applied in biomedical applications. Although anatomy-based approach can determine the skin deformation based on the change in geometry of underlying layers, it is usually time-consuming to determine the geometrical change of each anatomical layer. This article presents a physics-based approach to model human skin deformation using boundary element method (BEM). Given the magnitude of displacement between the skin layer and the underlying skeleton at the anatomical landmarks, the approach determines the displacement of each vertices of the human skin model by using the BEM. We demonstrated our results by modeling the skin deformation of human lower limb with jumping and walking motions. Experimental results have shown that the proposed method can deform the skin layer at interactive frame rates.

Keywords: interactive skin deformation, physics-based, boundary element method.
DOI: 10.3722/cadaps.2010.101-108

1 INTRODUCTION

Modeling human skin deformation is very important especially in the areas of computer graphics and human biomechanics. Nowadays, anatomy-based approach [1-3] is widely used to determine the skin deformation based on the deformation of underlying layers including skeleton, muscles, fatty tissues, ligaments, etc. The skin layer is then deformed based on the deformation of underlying layers. However, it is usually time-consuming to determine the deformation of each anatomical layer.

Methods that used to deform the human skin layer include geometry- and physics- based approaches. Geometry-based approach [4-5] such as Free Form Deformation (FFD) provides flexibility for the users to control deformations of models. The method is simple and fast but requires considerable skill to model realistic model. Physics-based approaches such as mass-spring system [6] and the finite element method (FEM) [7-8] can model skin layers according to its physical properties accurately. In [6], based on the deformation of geometric muscles, skin tissue is deformed by the mass-spring system. Manohar et al. [7] present a finite element modeling approach to model facial deformation.

In spite of a number of approaches have been adopted to model skin deformation, the methods are either labor intensive or time-consuming in computation. In addition, most of the method requires setting up a large number of correspondences between the skin and the underlying layers. This requires a higher performance computer for data storage and computation. This paper presents a physics-based approach to model skin deformation using the Boundary element method (BEM). Nowadays, BEM has seldom been used for performing interactive object simulation. However, the method is a good tradeoff between computation time and accuracy of simulation [9]. In addition, we attempted to model the skin deformation with only several correspondences with the skeleton. Given the magnitude of displacement between the skin layer and the underlying skeleton at only several anatomical landmarks, the skin deformation is then modeled by the BEM.

The remainder of this paper is organized as follows. In section 3 we describe our method for modeling skin deformation using the BEM. We present the experimental results in section 4. Section 5 concludes the paper.

2 METHODS

This article presents an approach to model skin deformation. Given the magnitude of displacement between the skin layer and the underlying skeleton at the anatomical landmarks on the skin layer, the deformation of human skin layer under different motions was determined using the BEM. In our approach, the transformation of the anatomical landmarks on the skin layer under different motions is firstly determined. Based on the transformation of the pre-defined anatomical landmarks, the deformation of the rest of the vertices on the skin layer is then modeled by the BEM.

2.1 Boundary Element Method

The BEM is a popular technique for engineering analysis, which can be found in many existing articles [10–11]. In order to simplify our investigation, the skin model is assumed to be linear elastic with isotropic and homogeneous material properties. In order to satisfy this assumption, the deformation of the skin layer that is the human motion between each time frame is small.

Given *N* nodes of the boundary model, the boundary integral equation can be expressed using matrix notation:

$$\mathbf{KU} = \mathbf{T}\,, \tag{1}$$

where **K** is the stiffness matrix with size equal to $3N \times 3N$, **U** and **T** are the vectors of displacement and traction respectively with size equal to $3N \times 1$. **U** and **T** contains the displacement and traction of each vertex of the element such that $\mathbf{U} = \left\{ u_{1x} \quad u_{1y} \quad u_{1z} \quad \cdots \quad u_{ix} \quad u_{iy} \quad u_{iz} \quad \cdots \quad u_{Nx} \quad u_{Ny} \quad u_{Nz} \right\}^t$ and $\mathbf{T} = \left\{ t_{1x} \quad t_{1y} \quad t_{1z} \quad \cdots \quad t_{ix} \quad t_{iy} \quad t_{iz} \quad \cdots \quad t_{Nx} \quad t_{Ny} \quad t_{Nz} \right\}^t$. In which, u_{ij} and t_{ij} denotes the three-dimensional (3-D) displacement and traction of the boundary model. The first subscript $i \in \left[1, N\right]$ denotes the index of the node of the skin model, the second subscript *j* denotes the *x*-, *y*- and *z*- directions. $\left\{\bullet\right\}^t$ denotes the transpose of the vector.

Since the object deformation problem requires only the displacement to be determined and tractions at all free elements are zero, Eqn. (1) can be expressed as

$$\mathbf{U}_U = -\mathbf{K}_{00}^{-1}\mathbf{K}_{01}\mathbf{U}_K\,, \tag{2}$$

where $\mathbf{U}_U$ and $\mathbf{U}_K$ be the vectors representing the unknown and known displacement. $\mathbf{K}_{00}$ and $\mathbf{K}_{01}$ be the sub-matrices of the stiffness matrix respectively, which can be computed by referring to [8].

In our problem, $\mathbf{U}_K = \left\{ u_{1x} \quad u_{1y} \quad u_{1z} \quad \cdots \quad u_{kx} \quad u_{ky} \quad u_{kz} \quad \cdots \quad u_{Nx} \quad u_{Ny} \quad u_{Nz} \right\}^t$ contains a set of N_k vertices with known displacement on the skin layer at the anatomical landmarks, u_{kj} , $k \in \left[1, N_k\right]$ denotes the index of the nodes at the anatomical landmarks. The size of $\mathbf{U}_K$ is equal to $3N_k \times 1$.

u_{kj} can be determined by the global and local deformation of the skin layer such that :

$$u_{kj} = G_{kj} + L_{kj} . \tag{3}$$

G_{kj} is the global deformation due to the transformation between the skin and skeleton during simulated motions. Suppose $v_{kj} = \left\{ v_{kx} \quad v_{ky} \quad v_{kz} \right\}^t$ be the 3-D Cartesian coordinate of the k^{th} node on the skin layer and $\hat{v}_{kj} = \left\{ \hat{v}_{kx} \quad \hat{v}_{ky} \quad \hat{v}_{kz} \right\}^t$ be the 3-D Cartesian coordinate of the k^{th} node on the skeleton corresponding to v_{kj} . Given the motion of the model, the transformation including the rotation matrix ***R*** and translation vector ***T*** of the nodes on the skeleton $\hat{v}_{kj}$ is therefore known, G_{kj} is computed by:

$$\left\{ G_{kx} \quad G_{ky} \quad G_{kz} \right\}^t = \left\{ v_{kx} \quad v_{ky} \quad v_{kz} \right\}^t - \left[R \left\{ \hat{v}_{kx} \quad \hat{v}_{ky} \quad \hat{v}_{kz} \right\}^t + T \right] . \tag{4}$$

L_{kj} is the local deformation of the skin layer due to inertial effects and deformations caused by underlying muscles. The magnitude of deformation L is randomly obtained from the normally distributed skin artifact function $N(\mu, \sigma^2)$ with mean value of μ and standard deviation of σ . The skin is locally deformed according to the direction of global deformation such that:

$$\left\{ L_{kx} \quad L_{ky} \quad L_{kz} \right\}^t = \frac{L \left\{ G_{kx} \quad G_{ky} \quad G_{kz} \right\}^t}{\left| \left\{ G_{kx} \quad G_{ky} \quad G_{kz} \right\}^t \right|} . \tag{5}$$

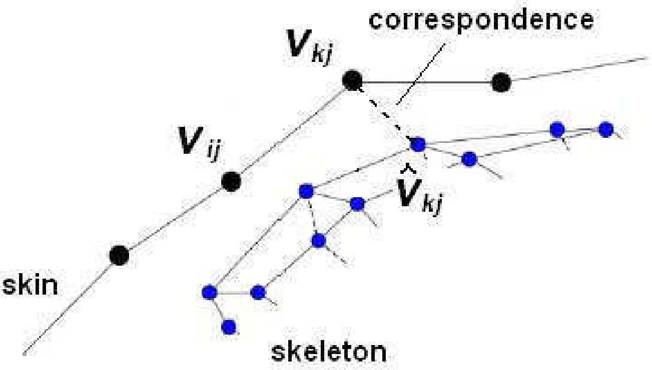

Fig. 1: The notations and the correspondence between the skin and skeleton.

Fig. 1 shows the notations and the correspondence between the skin and skeleton. By computing the displacement of each node *k* using Eqn. (3), $\mathbf{U}_K$ is known. Therefore, all the nodal values of the skin model $\mathbf{U}_U$ can be computed by Eqn. (2). Then, deformation of each vertex on the skin layer is obtained by interpolation.

3 EXPERIMENT AND RESULTS

In this article, the human lower limb model with shank and foot was used to demonstrate the proposed methodology. Fig. 2 shows the human lower limb model. The model was divided into a number of triangular elements. The model contained a skin layer and 28 bony structures (Tab. 1). The skin layer contained 606 vertices and 1208 triangles. The skin layer was deformed using the BEM with linear triangular elements. Fig. 3 shows the pre-defined anatomical landmarks on the skin layers [12]. In this article, lateral femoral epicondyle (LE), medial femoral epicondyle (ME), lateral malleolus (LM), medial malleolus (MM), the 5th metatarsal head (5H), the 1st metatarsal head (1H) were defined as the known displacement on the skin layer. The material properties of skin layer can be found in [13]. The displacement of the skin layer at the anatomical landmarks can be found in many biomechanics articles [14-16]. The average displacement of the anatomical landmarks on the skin layers was 5±1.6 mm [14].

Fig. 2: The lower limb model.

The skin layer was modeled in our system developed using Visual C++. The experiments were implemented on a personal computer with a Pentium Core 2 Duo 3.0 GHz CPU and 2 GB memory. To achieve interactive deformation of the skin layer, the stiffness matrix **K** and its inverse $\mathbf{K}^{-1}$ were pre-computed first. The time required for the pre-computation process was 244 seconds. Fig. 4 and 5 show the snapshots of modeling skin layer of the lower limb during jumping and walking motions respectively. The skin layer was deformed with 25 frames per second.

Model	*Number*	*Total number of*	
		Vertices	*Triangles*
Skin	1	606	1208
Bony structures	28	4797	9482

Tab. 1: The number of vertices and triangles for the skin and skeleton layers of the lower limb model.

Fig. 3: The pre-defined anatomical landmarks on the skin layers. LE: lateral femoral epicondyle, ME: medial femoral epicondyle, LM: lateral malleolus, MM: medial malleolus, 5H: the 5th metatarsal head, 1H: the 1st metatarsal head.

4 DISCUSSIONS

In this article, a physics-based approach using BEM to model skin deformation is presented. We demonstrate the methodology with a lower limb model. The model is only divided into skeleton and skin layer. Given the motion of the skeleton, and the deformation between the skin and skeleton, the displacement of the anatomical landmarks on the skin layer is known. The known displacements are used to determine the deformation of the rest of the vertices on the skin model using Eqn. (2). In our method, only a few numbers of correspondences are used. An experiment that models the skin layer of the lower limb during jumping and walking motions were demonstrated. Experimental result has shown that the BEM can model skin deformation with subjective good visual realism. The simulation was also performed in an interactive frame rate.

In this article, only six correspondences between the skin and skeleton layers were used. Although the method can model skin deformation during jumping and walking motions with subjective good visual realism, the relationship between the accuracy of modeling skin deformation and the number of correspondences was not known. In the future, we may consider determining the relationship between the accuracy of deformation and the number of correspondences. On the other hand in this article, only several frames of jumping and walking motions were demonstrated. We may also consider conducting more experiments on modeling skin deformation with more number of frames during different motions.

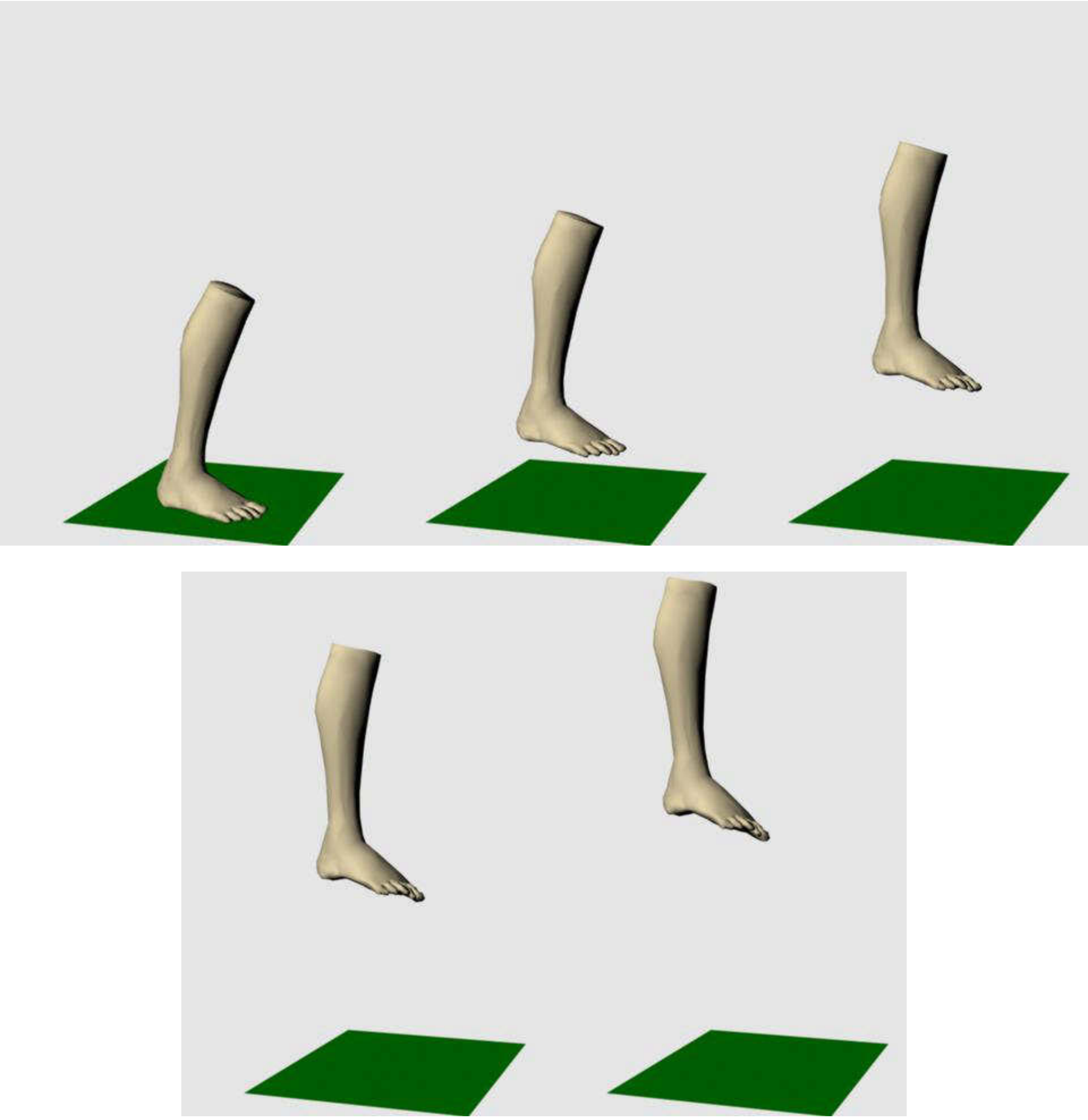

Fig. 4: Snapshots of modeling skin layer of the lower limb during jumping motion.

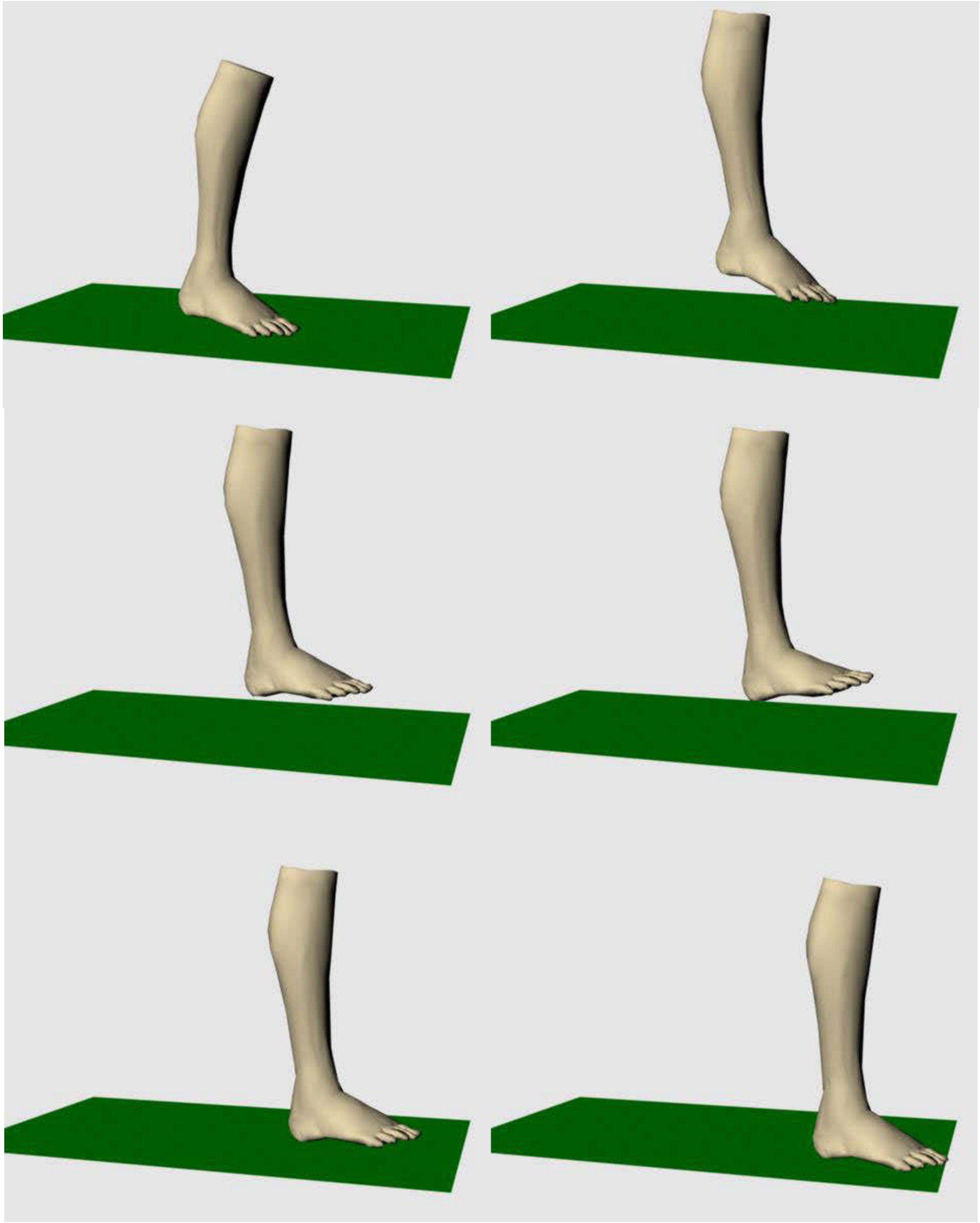

Fig. 5: Snapshots of modeling skin layer of the lower limb during walking motion.

REFERENCES

[1] Scheepers, F.; Parent, R. E.; Carlson, W. E.; May, S. F.: Anatomy-based modeling of the human musculature, In: Computer graphics proceedings, ACM SIGGRAPH, 1997, 163–70.

[2] Albrecht, I.; Haber, J,; Seidel, H .P.: Construction and animation of anatomically based human hand models, In: Proc. eurographics/SIGGRAPH symp. on computer animation, 2003, 98–109.

[3] Tang, Y.-M.; Hui, K.-H.: The effect of tendons on foot skin deformation, Computer-Aided Design, 39(7), 2007, 583-597.

[4] Sederberg, T.-W.; Parry, S.-R.: Free-form deformation of solid geometric models, In: SIGGRAPH, 20(4), 1986, 151–159.

[5] Singh, K.; Kokkevis, E.: Skinning characters using surface-oriented free-form deformations, In: Proceedings of Graphics Interface, 2000, 35–42.

[6] Albrecht, I.; Haber, J.; Seidel, H.-P.: Construction and animation of anatomically based human hand models, In: Proc. eurographics/SIGGRAPH symp. on Computer Animation, 2003, 98-109.

[7] Manohar, V.; Shreve, M.; Goldgof, D.; Sarkar, S.: Finite Element Modeling of Facial Deformation in Videos for Computing Strain Pattern, In Proceedings of the Nineteenth International Conference on Pattern Recognition, 2008, 1-4.

[8] Gourret, J.-P.; Thalmann, N.-M.; Thalmann, D.: Simulation of object and human skin deformations in a grasping task, Computer Graphics, 23, 1989, 21–29.

[9] James, D.L.; Pai, D.K.: ArtDefo: Accurate real time deformable objects, Proceedings of Computer Graphics, 1999, 65–72.

[10] Brebbia, C.-A.; Telles, J.-C.-F.; Wrobel, L.-C.: Boundary element techniques: Theory and applications in engineering, Springer-Verlag, 1984.

[11] Tang, Y.-M.; Zhou, A.-F.; Hui, K.-H.: Comparison of FEM and BEM for interactive object simulation, Computer-Aided Design, 38(8), 2006, 874-886.

[12] Vaughan, C.-L.; Davis, B.-L.; O'Conner, J.-C.: Dynamics of Human Gait: Human Kinetics, Champaign, 1990.

[13] Abé, H.; Hayasji, K.; Sato, M.: Data book on mechanical properties of living cells, tissues, and organs. Springer, 1996.

[14] Sangeux, M.; Marin, F.; Charleux, F.; Dürselen, L.; Ho Ba Tho, M.: Quantification of the 3D relative movement of external marker sets vs. bones based on magnetic resonance imaging, Clinical Biomechanics, 21(9), 2006, 984-991.

[15] Alexander, E.-J.; Andriacchi, T.-P.: Correcting for deformation in skin-based marker systems. Journal of Biomechanics, 34, 2001, 355-361.

[16] Cappozzo, A.; Catani, F.; Leardini, A.; Benedetti, M.-G.; Della Croce, U.: Position and orientation in space of bones during movement: experimental artefacts, Clin Biomech, 11(2), 1996, 90-100.