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Analysis of Skin Movements with Respect to Bone Motions using MR Images

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Abstract – This paper describes a novel experiment that measures skin movement with respect to the flexional motion of a hand. The study was based on MR images in conjunction with CAD techniques. The MR images of the hand were captured in 3 different postures with surface markers. The surface markers attached to the skin were employed to trace skin movement during the flexional motion of the hand. After reconstructing 3D isosurfaces from the segmented MR images, the global registration was applied to the 3D models based on the particular bone shape of different postures. Skin movement was interpreted by measuring the centers of the surface markers in the registered models.

***Keywords*: Skin movement, Motion analysis, MR images, 3D surface reconstruction, Registration, CAD, Index finger**

1. Introduction

Anatomical knowledge such as bone shape, positions, orientations, and associated soft tissues plays an important role in understanding mechanics of hard and soft tissues. The mechanism of bone motion is well known, but the movement of the skin relative to underlying bones is poorly understood. Most kinematic data for motion analysis have been gathered with surface markers. The surface markers, which are usually photosensitive, are attached on the skin to trace the motion of bones. Optical measuring systems determine the position of these markers in the calibrated space during motion [1, 3, 9, 10]. However, the skin movement can affect the accuracy of measuring the bone motion by the optical system, because the actual bone motion and the surface markers' movement can be different. This error is called 'skin movement artifacts'. Based on this study, the error tendency and quantity can be identified.

The previous studies for motion analysis require invasive experiments or cannot be applicable to a living subject. To avoid invasive experiments, medical imaging techniques have been used to collect anatomical data for motion analysis. Medical imaging techniques have the advantage of capturing the internal geometry of living subjects in high resolution [4, 12, 13]. We are looking forward to developing the method that is safe to the living subject and obtain *in vivo* data. In this research, a novel experiment based on MR scanning and computer aided design (CAD) techniques was made to investigate skin movement with respect to the flexional motion of the hand. The MR images of the hand were captured in 3 postures using 36 surface markers attached on the skin of the hand. Surface modeling techniques were used to reconstruct the 3D polygonal models from the segmented MR images, while global registration technique was used to align the 3D models of different postures.

2. Methods

2.1. MR scanning of the hand

The male subject, whose hand size was approximately 20 cm long, had no clinical disorders, consented to use his anatomical data for scientific purposes. MR images of the hand were scanned in three postures with surface markers. Two surface markers were attached on each knuckle and a total of 36 surface markers were used in the MR scanning of the hand. Fig. 1 shows the three postures of the hand. Fig. 1(a) shows the first posture in which all fingers were straightened without touching each other. The second posture (Fig. 1(b)) shows the hand holding a cylindrical jig. The last posture (Fig. 1(c)) shows the hand holding a cylindrical jig with smaller radius than that of the second posture. The thumb in the third posture is inside of the other fingers. The cylindrical jigs were developed to make consistent control of postures of the hand during a long scanning time. They reduced motion blur artifacts by helping the subject maintain the consistent posture for 12 minutes of MR scanning.

Fig. 1(d) shows the corresponding MR images of the

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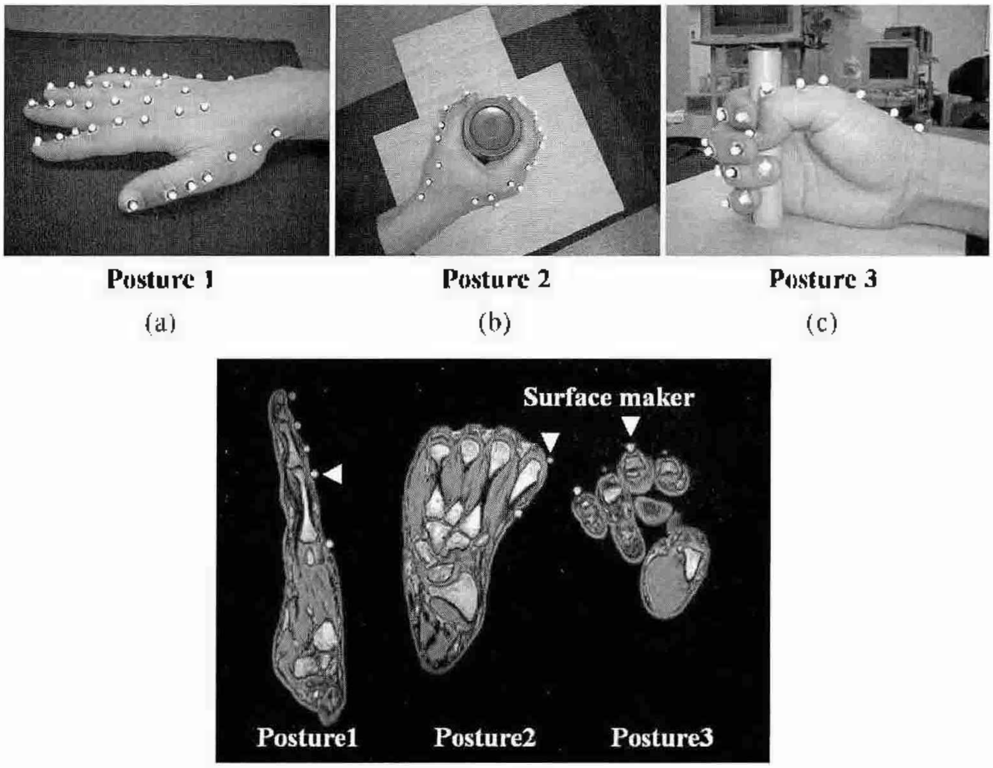


(d)

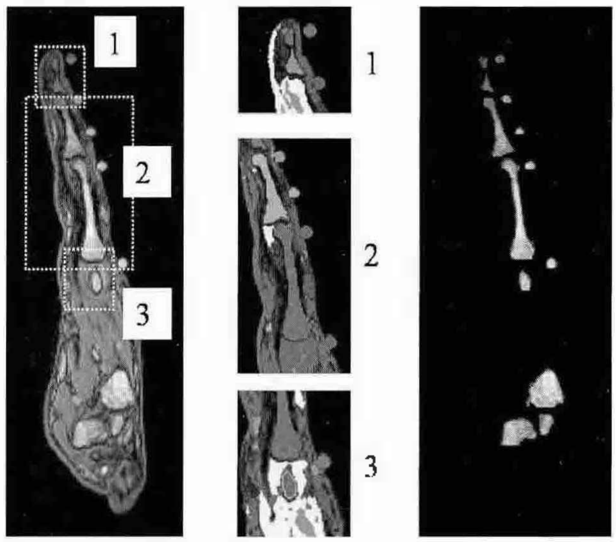
Fig. 1. MR scanning of the hand with surface markers in 3 postures: (a) Posture 1, (b) Posture 2, (c) Posture (3), (d) Typical MR images of the three postures.

postured hands. The surface markers in the MR image looked like small circles, which could be identified by arrows in the figure. The MR scanner of Siemens Magnetom machine was used to obtain MR images with magnetic strength field of 0.95, time repetition of 11.4 ms, time echo of 4.4 ms, and field of view (FOV) of 250 mm. For each posture of the hand, one hundred sliced images were generated with slice interval of 1.5 mm. The sectional image was 256×256 pixels in size, 8 bit per pixel, and its physical spacing of pixels was 0.98 mm. The slice plane of posture 1 was parallel to the longitude direction of the fingers, and the slice planes of posture 2 and posture 3 were perpendicular to the longitude direction of the fingers.

2.2. MR image processing

An in-house software called 'MediSurf' has been developed for processing the MR images. The software has the capability of file conversion from the scanner to our proprietary image format, the segmentation of ROI, and the isosurface generation.

Fig. 2 illustrates the semi-automatic segmentation that distinguished bones and surface markers from soft tissues. First, the pixels were removed by threshold of Th_{low}. The determined Th_{low} value was 60. The next step was to remove pixels representing soft tissues. The contour tracing method was used to identify edges of objects in the image. Comparing with conventional edge detector operators such as Prewitt, Sobel, Canny, and Marr-Hildreth [5, 6], it resulted in closed edges of the detected object. Then, uninteresting objects were removed by manually selecting the inside of closed edges.



(a) (b) (c)

Fig. 2. Example of the segmentation that extracts bones and surface markers: (a) MR images of the hand. (b) Level-set curves with various isovalues. (c) Segmentation result.

In contour tracing, the level-set based algorithm was used to trace boundaries by connecting successive edge vertices. The initial level-set is constructed by the marching square algorithm, which is the 2D version of marching cube [7]. It produces *unordered* edge segments of boundaries given the isovalue. The closed or open contour is then identified by traversing the unordered edge list. Fig. 2(b) shows the identified objects filled with different colors. In the example, three isovalues were used. The distal phalanx was segmented with level-set of 50. The proximal phalanx and the middle phalanx were segmented with the level-set of 72. The metacarpal bone was segmented by the level-set curve of 98.

The result of the segmentation was not always satisfactory in detecting the desired objects, since MR images themselves gave low contrast between bones and soft tissues. Hand drawings of uninteresting objects were often necessary. One benefit of MR images for the segmentation of bones was the clear black gaps of the cortical bone, which is the outer layer of the bone. Since the cortical bone was represented by a low pixel value in MR images, there existed small gaps between bones and soft tissues (Fig. 2). It allowed easier segmentation by selecting gaps of cortical bones indicated by the arrow in the figure.

2.3. Isosurface generation from the segmented MR images

After the segmentation of bones and surface markers, isosurfaces of interesting objects were reconstructed using our software, 'Medisurf'. It contains the marching cube algorithm [7] that is also known as '3D contouring' or 'polygonization of a scalar field'. This method is not only very simple in terms of data structure and its implementation, but also provides high-speed computation since it works on the predefined lookup table. The lookup table enumerates all possible topological states of a cell, given combinations of scalar values at the cell vertex. Since one grid cell is defined by 8 vertices and scalar values at each vertex, the number of topological state is equal to 2^8 (=256) cases. These 256 possible configurations of triangle can be reduced to 15 cases due to the symmetry such as rotation and mirroring. For each grid cell, the marching cube algorithm tries to create a set of planar triangles that best represents the isosurface of the cell. If one or some values at vertices of the cell are less than the user specified isovalue, this cell should contribute to construct the isosurface. Each cell is treated independently to each other in order to construct whole isosurfaces of entire volume. The improved algorithm based on oversampling method in digital signal processing is published elsewhere [11].

The isovalue determined by the user affects the accuracy and size of the reconstructed isosurfaces. When the isovalue is determined by a large value, shape information of an interesting object can be lost. In addition, the size of generated isosurfaces becomes smaller than that of the subject. When a smaller isovalue is used, the isosurfaces can include uninteresting objects whose pixel values are greater than the specified isovalue. The size of the isosurface can be bigger than that of the subject. The optimal isovalue represents the external boundaries of bones and surface markers. In reconstructing complete isosurfaces, the thresholds with various pixel values are tried to determine the proper isovalue. The criteria for determining the optimal isovalue are that bones and surface markers are maintained while soft tissues are separated from the interesting objects.

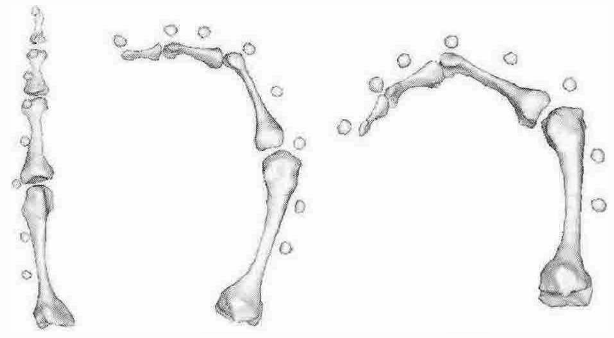


Fig. 3. Reconstructed 3D models of the index finger and surface markers in 3 postures.

Fig. 3 gives the isosurfaces of the index finger bones and surface markers generated by the software. The original isosurfaces from MR images were of huge file size and often involved uninteresting objects with errors such as non-manifold edges, overlapped triangles, and holes. The polygon-based algorithms such as decimation, hole-filling, removal of triangles, and Laplacian smoothing were applied to refine the quality of isosurfaces. It was also possible to generate skin surfaces from MR images since MR images contained information on the shape of the skin.

2.4. Registration based on the shape of bones

The registration integrates several objects from different coordinate systems into a common coordinate system. It calculates the transformation matrix to align local coordinate systems into the reference coordinate system. In this study, the local coordinate (or the bone coordinate) systems vary depending on the posture of the hand. The bone motion is assumed by a rigid body motion, although the skin is deformable. By merging different bone coordinate systems, the skin movement can be traced under the situation that the particular bone is fixed during motion. This assumption makes it possible to use the registration method of using a particular bone and to trace skin movement by measuring the changed positions of surface markers after the registration.

There are two approaches in registration, namely the *feature based* registration and the *global* registration. In feature based approach, the user select more than 3

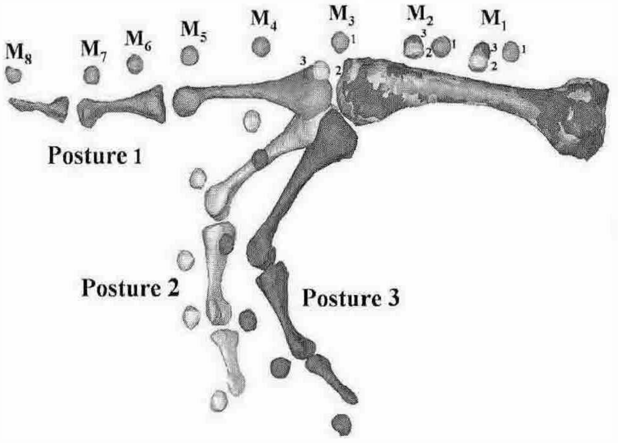


Fig. 4. Registration based on the metacarpal bone of the index finger: M_i represents the i-th marker attached on the skin, and colors of the model represent the different postures.

common vertices of the objects to calculate the transformation matrix. The vertices on the sharp edge, sphere centers, or planes can be used as feature points. On the other hand, the global registration uses the Iterative Closest Point (ICP) algorithm [2, 12] to calculate the transformation matrix by repeatedly minimizing least square error between the vertices of the floating object and the reference object.

In the study, one could use anatomical landmarks selected by the user's prior knowledge or principal axes by calculating eigenvectors of the covariance matrix and the centroid of the model [12]. These methods are easy to implement, but they are not suitable due to unpredictable errors. The errors occur as partial volume effects and/or different slicing directions of the subject in multiple MR scanning. The semi-automatic segmentation and the 3D reconstruction also contained errors. To reduce these errors, the global registration method was used. The metacarpal bone of posture 1 was used as the reference model, and the others used as the floating model for registration. The initial transformation matrix was estimated by selecting three common vertices. The global registration was then applied to the initial registration.

Fig. 4 shows the result of the global registration based on the metacarpal bone of the index finger. 3D models colored green, yellow, and red represent postures of 1, 2, and 3 respectively. M_i is the i-th surface marker on the index finger. The average alignment error that is the least square distance between floating and reference models was 0.098 mm and the standard deviation was 0.072 mm.

3. Results

After registration of the postured hand model, the surface markers were fitted to spheres to analyze the skin movement with respect to the flexional motion of the hand. The center and radius of the fitted spheres were calculated. Table 1 gives the result of centers and radii of the surface markers on the index finger.

The result was interpreted as the flexional motion of the index finger while the metacarpal bone was fixed. The movement of M_1 and M_2 represented the skin

Table 1. Center and radius of surface markers after the registration

Markers	Center of the marker (x, y, z)			Radius of the marker (mm)			
	Pose 1	Pose 2	Pose 3	Pose 1	Pose 2	Pose 3	$\mu\pm\sigma^{(*)}$
M_1	(110, -43.4, -27.7)	(112, -37.7, -21.3)	(108, -36.4, -24.5)	2.51	2.49	2.56	2.52±0.04
M_2	(111, -27.3, -20.4)	(113, -22, -15.8)	(110, -20.5, -17.7)	2.51	2.45	2.48	2.48±0.03
M_3	(116, -5.06, -7.69)	(114, -3.4, -0.145)	(112, -1.56, 0.956)	2.4	2.45	2.41	2.42±0.03
M_4	(112, 13.4, 1.25)	(101, 9.81, 14.3)	(99.7, 3.62, 21.1)	2.49	2.5	2.46	2.48±0.02
M_5	(112, 28.8, 11.4)	(90.7, 18, 29.6)	(91.4, 3.48, 40.7)	2.46	2.48	2.49	2.48±0.02
M_6	(111, 40.2, 19.4)	(83.9, 12.9, 46.4)	(87.3, -9.89, 53.4)	2.38	2.39	2.54	2.44±0.09
M_7	(109, 49.4, 26.2)	(79.6, 5.76, 56.7)	(85.3, -22.5, 59.1)	2.34	2.49	2.63	2.49±0.15
M_8	(109, 67.5, 35.2)	(73.9, -9.58, 69.8)	(85.2, -43.7, 64.4)	2.15	2.37	2.49	2.34±0.17

(*): μ = mean, σ = standard deviation

Table 2. Volume and surface area of the index finger in different postures

Bones	Volume (mm^3)				Surface area (mm^2)			
	Pose 1	Pose 2	Pose 3	$\mu\pm\sigma^{(*)}$	Pose 1	Pose 2	Pose 3	$\mu\pm\sigma^{(*)}$
Metacarpal bone	5618.5	5729.8	5814.1	5720.8±98.1	1245.5	1262.3	1291.3	1266.3±23.2
Proximal phalanx	2097.1	2051.9	1997.4	2048.8±49.9	619.8	597.9	604.9	607.5±11.2
Middle phalanx	636.2	646.3	660.1	647.5±11.0	277.0	272.7	277.1	275.6±2.5
Distal phalanx	149.4	195.0	193.1	179.2±25.8	105.4	124.4	119.1	236.2±9.8

(*): μ = mean, σ = standard deviation

movement associated to the metacarpal bone. The centers of M_1 and M_2 were the locus of the associated skin movement for the flexional motion moving through postures 1 to 3. The flexional motion of posture 1 to 2 shifted the skin along the metacarpal bone, and the motion of posture 2 to 3 fell down the skin. The skin movement of posture 1, 2, and 3 was likely to form circular locus on the metacarpal bone. The average moving distance of the skin associated with the M_1 and M_2 during flexional motion of index finger was 5-8 mm. The distance can be varied depending on the size of subject's hand. However, the direction of the skin movement is consistent regardless of the subjects.

The geometric error of the result could be evaluated by checking the radius of the surface markers, and the volumetric and surface area errors of bones. The results shown in the right most column of Tables 1 and 2 could be used to evaluate the geometric error of the result. The standard deviation of the radii of the surface markers was 0.02-0.17 mm. The standard deviations of the volume and surface area were 11~98 mm^3 and 2.5~23 mm^2, respectively. The error was in a reasonable range considering the slice interval for MR images of 1.5 mm.

4. Conclusion

This study presented the methodology for analyzing skin movement with respect to the flexional motion of the hand. The 3D *in vivo* data was acquired through MR scanning of multiple postures of the hand. The in-house software has been developed to process MR images and to generate isosurfaces. Global registration was used to align the generated isosurfaces of multiple postures. The centers of surface markers represented the locus of skin motion during flexional motion. The proposed approach allowed direct, accurate, fully 3-dimensional, and *in vivo* data to be used for biomedical applications without invasive experiments.

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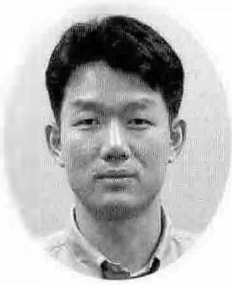

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