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AUTOMATIC DETERMINATION OF PATELLOFEMORAL KINEMATIC PARAMETERS THROUGH X-RAY IMAGE PROCESSING

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patellofemoral, radiograph, kinematics, sulcus angle, Merchant view

ABSTRACT
Examination of plain Merchant-view X-rays of the patellofemoral joint is often used to diagnose patellofemoral joint malalignment and to qualify the pathology. As digital image processing becomes more widespread, an image processing algorithm is being developed for medical personnel to easily display, manipulate and analyze digitized plain Merchant-view X-ray films on personal computers. The method provides measurement of the kinematic parameters: sulcus angle (SA), patellofemoral congruence angle (PFC), lateral patellar angle (LPA), patellar rotation angle (PR), and lateral patellar displacement (LPD). Smooth edges of the patella and the femur are obtained by using image enhancement, edge detection and morphological thinning techniques based on the thresholds chosen manually for boundary detection. Six landmarks for determining the kinematic parameters are marked automatically on the edges of patella and femur. Parameter measurements for twelve X-ray films of six patients are calculated for analysis and comparison with hand calculated parameters. The goal is develop an algorithm that can evaluate the geometry of the patellofemoral joint, and is cost effective.

INTRODUCTION
Abnormalities of the patellofemoral joint are considered to be among the most frequently encountered group of internal derangements of the knee. Clinical confirmation of the diagnosis of patellar malalignment is difficult, because the signs and symptoms may mimic those of other forms of internal knee derangements[9]. Therefore, accurate noninvasive assessment of the patellofemoral joint can play an important role in the clinical management of this sometimes confusing group of conditions [3].

Radiographic evaluation of the patellofemoral joint has evolved considerably in the past decade, largely because of the advent of cross-sectional imaging (e.g., CT and MR imaging) [8]. Plain radiographs were the only imaging modality at a doctor's disposal formerly. Initial radiographic examination relied solely on tangential views with the knee in flexion greater than 30°[6]. Physical examination and plain radiography typically suffice in the definitive diagnosis of patellar malalignment for most patients with knee pain[2], unless, when subluxation is suspected but not seen on plain radiographs, MRI or CT imaging should be used to provide the necessary information. The challenge then exists in choosing the least expensive imaging technique that provides the most definitive information[5].

Computerized tomography (CT) has been recognized as an excellent technique for evaluating the patellofemoral joint because axial images can be obtained during the initial degrees of knee flexion[10]. This capability is crucial, because it is during this range of motion that the patella has a tendency to be
unstable and patellar tracking abnormalities are the most apparent[9]. Magnetic resonance imaging (MRI) contributes to the determination and evaluation of patellofemoral abnormalities in a fashion similar to that of CT, with certain advantages over CT. It does not require ionizing radiation and is able to provide information about important soft-tissue structures that are essential for understanding the cause of abnormal patellar tracking. Kinematic MRI studies, which clearly display the images in forward and reverse sequence, allow us to better appreciate the functional positions of each patella in relation to the trochlear groove through the various angles of flexion studied[9]. CT and MRI scanning have several advantages over plain radiography, however, they have disadvantages such as inconvenience, cost (especially MRI), and radiation (CT)[5].

Current methods for quantifying the geometry of the femur and patella require identification of specific landmarks. It is necessary to select landmarks in order to calculate the parameters associated with the patellofemoral joint. Rather than "eyeball" the X-ray image of a patellofemoral joint, some measurements have been proposed as quantitative assessment of the position of the patella relative to the femoral trochlear groove. These quantitative parameters are currently used to clarify disorders such as, chondromalacia patellae, subluxation of the patella and the patellofemoral osteoarthritis[7]. At present, these measurements are carried out visually by human operators so that it is tiresome and often subjective. Many physicians are seeking an effective way to automate and speed-up the diagnosis. The main purpose of this research project is to develop an algorithm for determining anatomic measurements of the patellofemoral joint from X-ray images. This will give the physician the ability to characterize abnormalities of the knee based on quantitative values of these parameters. In this paper, an algorithm which can calculate five commonly used anatomic parameters from plain radiographs is presented.

METHODS AND MATERIALS

Image Acquisition

Patients are X-rayed using the procedure described by Merchant et al.; Subjects are situated with the knee held at 45° of flexion by an axial viewer (Specialty Centers for Orthopaedic and Rehabilitative Excellence, 1550 E. Country Line Rd, Indianapolis, IN 46227). The cathode tube is set at 152.4 cm from the patella with a field size of 15.2 x 15.2 cm²[8]. The crosshair illumination by the lamp is set on the anterior-most aspect of the patella. Exposure variables are: 100mA, 0.05s, and 100kV. For each patient, the right and left knees are X-rayed once. All X-rays are taken by a certified X-ray technician.

It is necessary to transfer analog images to digitized form so that the images will be recognized by the computer. A digital image is obtained by sampling an analog image. The amplitude of the digital image is quantized to 256 levels (which can be represented by eight bits). Each level is denoted by an integer, with 0 corresponding to the darkest level and 255 to the brightest.

The illuminated X-rays are first acquired by using a Panasonic video camera, which is set about 1 meter in front of the illuminator. Digital images are converted and displayed on the monitor connected to a Macintosh Quadra 840 with the aid of an image utility, VideoViewer 1.1. Using GraphicConverter V2.6 (Snail-Mail Lcmke Software), all images are stored as TIFF files. The file size is 320*240 pixels with resolution approximately 0.25mm (0.01 inches), occupying about 75KB memory for each original image. The programs for x-rays enhancement, segmentation, edge detection and parameter calculation are written in the environment of Matlab Version 5.1 (MathWorks, Inc., Natick, MA).

Parameter Calculation

In this study, a brightness and contrast adjustment is accomplished using a histogram equalization. The mapping function of gray levels is

\[ f(x) = \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}} - f_{\text{min}}} x + \frac{f_{\text{min}}}{f_{\text{max}} - f_{\text{min}}} \]

where \( f_{\text{max}} \) and \( f_{\text{min}} \) are the desired maximum and minimum gray levels. This method is not affected by the difficulty of observing abnormal bone density in a wider contrast image.

Images are typically subject to a large amount of noise due to the presence of outliers that can cause the type of noise is to apply a low-pass filter to remove noise. Median and mean filtering[10] can be used to reduce noise and impulse noise, which varies in different sizes and shapes.

A segmented adaptive thresholding approach is applied to each pixel. Pixels labeled in the image depend on whether the pixel value is less than a threshold value chosen in the graylevel image histogram. Through observation of a large number of threshold T1 directly, the boundaries of the patellar boundaries, and other bone structures in the same way as the threshold value not only maximizes the signal-to-noise ratio associated with the bone structures.

In order to make the borders of the bone structures easier to observe, the edges to outline the bone structures is detected by a technique, which indicates that there may be one characteristic edge pixel within an image profile that can be determined by using a 8 connected point or by looking at the image edge methodically.

In this study, the edge detection was done using a Gaussian filter approximating for differentiation. An edge detection algorithm implemented by Schwartz et al.
Parameter Calculations

In this study, a linear autoscaling mapping function[1] is used to modify the image, enhancing its brightness and contrast making features observable that are invisible in the original image. It is accomplished using a one-to-one mapping of the original graylevels to a new desired range of graylevels. The mapping function that autoscales the input graylevels of an image to predetermined range of graylevels is

$$p_x = \frac{(max-min)(finx-fmin)}{(q_k-fmin)+min}$$

where $finx$ and $fmin$ are the maximum and minimum graylevels found in the input image, and $max$ and $min$ are the desired maximum and minimum graylevels in the output image. Figure 2 shows the effect of autoscaling on the original image given in Figure 1. The low brightness image of Figure 1 shows the difficulty of observing details of the patellar and femur joint. Figure 2 is a higher brightness version with wider contrast image, the detail features are now clearly visible.

Images are typically corrupted with noise. In this study, a 5 x 5 mean filter is used to reduce a large amount of noise at the expense of attenuation or eliminating high frequency components. The difficulty of mean filtering is that it very susceptible to outlier noise since the averaging is biased by the presence of outliers that drastically deviate from the normal value. An alternative solution to remove this type of noise is to apply nonlinear methods, such as median filtering, which preserve important edges and remove noise. Median filtering is particularly effective in reducing outlier type noise, such as impulsive, or salt-and-pepper noise. Figure 3 is the output image of original noise degraded image processed by 5 x 5 mean filtering and 3 x 3 median filtering. It shows that smooth filtering clearly reduces the film-grain noise and impulse noise, but at the same time it blurs the image. It may be useful to try several filters of different sizes and choose the best of the resulting images.

A segmented black-and-white image is generated using a predetermined graylevel as a decision criteria and applied to the entire graylevel image. It is accomplished by scanning the image pixel by pixel. Pixels labeled 1 correspond to object, whereas pixels labeled 0 correspond to background, depending on whether the graylevel of that pixel is greater or less than the value of threshold. The threshold value chosen depends on the desired features to be segmented from the other features present in the graylevel image. Segmentation should stop when the patella and femur have been isolated.

Through observation of the graylevels of the intensity image, the first step is to manually choose a threshold $T1$ directly from the enhanced image(Figure 3). Threshold $T1$ is used to segment femur and patellar boundaries, which include five landmarks: point M, L, U, T, P. The next threshold $T2$ is chosen in the same way as $T1$ to segment the boundaries which include landmark point O. A best threshold value not only maximizes the information present in the boundaries but also minimizes the error associated with the selection of a threshold value.

In order to locate the six landmarks on the border of femur and patella, it is required to extract the edges to outline the shape of femur and patella. The presence of an edge within a grayscale image indicates that there is a change in the graylevels between regions. The deviation of the graylevel change within an image provides a means of detecting an edge. It is reasonable to consider that the edge point can be determined by looking for the local extremum (maximum or minimum) of first derivative of the point or by looking for a zero crossing of the second derivative of the point where it changes its sign.

In this study, a Marr and Hildreth edge detection operator is applied. Marr and Hildreth suggested using a Gaussian function for bandlimiting the original image to reduce the effect of noise, the Laplacian for differentiation. Edges are then detected by zero-crossing points[6].

Morphological thinning creates the skeleton of the image(Figure 4). The approach is implemented by successively iterating over a set of elements until one pixel wide lines remain that
describe the skeleton of the object. The edges of the femur and patella after smooth thinning are separated and reduced in width to a single pixel. For easy manipulation, the coordinate locations of each of the pixels that define the edges are grouped together to form sets that completely describe the edges.

In order to calculate the kinematic parameters associated with the patellofemoral joint, the first requirement is to locate the six landmarks. From the Merchant view, there are six landmarks with three on the femur and three on the patella from each X-ray (Figure 5): the highest point on the medial condyle(M), the highest point on the lateral condyle(L), the lowest point of the patellofemoral groove(O), the posterior-most point of the thickest aspect of the patella(P), the medial-most point of the patella(U), and the lateral-most point of the patella (T). Figure 6 displays the six landmarks found on the patellofemoral joint. These 6 parameters are defined in reference 11, Waite and Gao.

RESULTS

The data that are of particular interest for this study are sulcus angle(SA), patellofemoral congruence angle(PFC), lateral patellar angle(LPA), patellar rotation angle(PR), and lateral patellar displacement(LP). In order to assess the accuracy and flexibility of the algorithm over different images, twelve X-rays are tested and the computer calculated results are compared with manual measurements. The results are illustrated in Table 1.

Table 1. Results comparison between computer and hand calculated parameters

<table>
<thead>
<tr>
<th>Subject</th>
<th>SA(°)</th>
<th>PFC(°)</th>
<th>LPA(°)</th>
<th>PR(°)</th>
<th>LPD(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Right</td>
<td>134</td>
<td>138</td>
<td>97</td>
<td>-20</td>
<td>27</td>
</tr>
<tr>
<td>1-Left</td>
<td>137</td>
<td>140</td>
<td>98</td>
<td>-10</td>
<td>36</td>
</tr>
<tr>
<td>2-Right</td>
<td>144</td>
<td>160</td>
<td>89</td>
<td>-10</td>
<td>-43</td>
</tr>
<tr>
<td>2-Left</td>
<td>140</td>
<td>150</td>
<td>93</td>
<td>-11</td>
<td>31</td>
</tr>
<tr>
<td>3-Right</td>
<td>170</td>
<td>172</td>
<td>99</td>
<td>-1</td>
<td>-59</td>
</tr>
<tr>
<td>3-Left</td>
<td>162</td>
<td>161</td>
<td>99</td>
<td>-18</td>
<td>53</td>
</tr>
<tr>
<td>4-Right</td>
<td>145</td>
<td>157</td>
<td>92</td>
<td>12</td>
<td>44</td>
</tr>
<tr>
<td>4-Left</td>
<td>158</td>
<td>152</td>
<td>96</td>
<td>28</td>
<td>68</td>
</tr>
<tr>
<td>5-Right</td>
<td>153</td>
<td>164</td>
<td>93</td>
<td>15</td>
<td>65</td>
</tr>
<tr>
<td>5-Left</td>
<td>159</td>
<td>154</td>
<td>97</td>
<td>16</td>
<td>55</td>
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<tr>
<td>6-Left</td>
<td>138</td>
<td>153</td>
<td>89</td>
<td>28</td>
<td>-19</td>
</tr>
</tbody>
</table>

DISCUSSION

As demonstrated, the recognition and extraction algorithm requires an adaptive threshold, and the algorithm uses two thresholds. The result shows that the computer calculated values are more accurate than the hand calculated values. Other parameters indicate that carefully studying the variation in the measurements could lead to improved accuracy.

Figure 1. Original X-ray image

Figure 2. Processed X-ray image

Figure 3. Normalizer

For final practice, the ability to adjust the range of normal values can be developed.

Figure 4. Diagram of the patellofemoral joint
DISCUSSION

As demonstrated in figures one through four, the algorithm which has been developed can recognize and extract the basic shape of the patellofemoral joint from X-ray images. The current algorithm requires an operator to select threshold boundaries on-screen using a mouse. Once the thresholds have been determined, the program can calculate the six anatomic parameters. The current algorithm uses two thresholds to choose the six landmarks.

The result shown in Table 1 indicates that values of the sulcus angle agree reasonably well with hand calculated values. The range of accuracy is 89 to 99%. Agreement with hand calculated values of other parameters indicates that additional work needs to be done to improve the algorithm and to more carefully study the variability between multiple clinicians.

![Figure 1. Original Image](image1)

![Figure 2. Autoscaling](image2)

![Figure 3. Noise Reduction](image3)

![Figure 4. Edge Detection & Thinning](image4)

The goal of the algorithm presented is to provide an automatic and objective method for clinicians to obtain quantitative anatomic parameters from Merchant-View X-ray images. The current method of manual calculation of these parameters allows for subjectivity in choosing landmarks, resulting in between-clinician variability. In the automatic method that is proposed, the choice of a graylevel threshold, which defines the boundaries of the femur and patella, is critical to the eventual success or failure of the analysis. The determination of the optimum threshold is difficult because the graylevels of the six landmarks may not be well separated from the background. Also, the threshold level at each of the six landmarks may have a different value. The next step in this study will be to develop a more reliable method of automatically choosing thresholds at each landmark.

For final practical use, a more friendly interface should be designed. The physicians should have the ability to adjust contrast, rotate the image, zoom in/out on images, print images and archive images. In order to expedite the evaluation of the patellar abnormalities, it will eventually be desirable to set a range of normal values for those most common anatomic parameters based upon statistical studies on
large group of normal patellofemoral joints. On the other hand, determining ranges of each parameters for different kinds of patellofemoral malalignment, such as chondromalacia, subluxation and osteoarthritis, will also be helpful.

References