Design and Implementation of Gradient Vector Flow Snake to Detect a Reference Object in Pelvic X-Rays for Preoperative Total Hip Arthroplasty Planning Application

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The main interest of this research project is to promote automation in performing preoperative planning for hip joint replacement surgery using a special medical image viewing software, ViewPro™. Preoperative planning is performed to carefully prepare the surgery and to accurately select the hip implants. The first step of preoperative planning is to calibrate the x-ray image to adjust the magnification factor. A femoral head implant is used as magnification factor reference. Automation is introduced by developing an algorithm to automatically detect this reference object in the image. The algorithm used for performing the automatic detection of the reference object is gradient vector flow (GVF) snake. A study has been performed to compare the newly developed semiautomatic algorithm to the old manual calibration algorithm. The results show a close relation between the two algorithms (less than 1% of average relative difference). It is concluded that the developed semiautomated algorithm can be used as an alternative for performing the manual calibration.

KEY WORDS: Preoperative planning, total hip arthroplasty, snake algorithm, gradient vector flow

INTRODUCTION

Musculoskeletal diseases are commonly found in elderly people. The hip joint is frequently the focus of severe degeneration, which can be a reason to surgically intervene. If the diseased joint causes severe pain and leads to functional impairment, a hip joint replacement can be considered. This surgical intervention is often referred to as total hip arthroplasty.

Preoperative planning is performed both to anticipate the specific anatomy of the patient and to determine the component sizes necessary to recon-

struct the hip joint as desired.¹⁻⁵ At the University Medical Center Groningen (UMCG), preoperative planning has been performed using HyperOrtho™ software (Rogan-Delft B.V., Veenendaal, The Netherlands). Unfortunately, after a period of time using this software, some drawbacks became apparent. Some of the tools are not user-friendly and the overall process needs a considerable amount of user interference. Therefore, a new software package has been designed and implemented, ViewPro™ (Rogan-Delft B.V., Veenendaal, The Netherlands) to overcome the problems of the old software. The orthopedic preoperative planning should again be implemented as a module into this ViewPro™ software package and a more semiautomatic planning should be achieved. The first step of the

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implementation, as described in this article, focuses on the introduction of automation of the start of the preoperative planning: calibrating the magnification factor of the hip x-ray image.

To perform the semiautomatic calibration, object detection is carried out using a gradient vector flow snake algorithm.^{6,7} The gradient vector flow snake is a modification of the snake algorithm,⁸ which is an already established tool for object detection. Applying semiautomatic calibration significantly reduces the manual interference and, therefore, enhances user-friendliness.

TOTAL HIP ARTHROPLASTY

In degenerative disease of the hip joint the cartilage tissue that lines the articulating bony parts of the joint are damaged. In the hip joint the femoral head articulates with the acetabulum (part of the pelvis that encloses the femoral head). If the degenerative changes become symptomatic with increasing damage to the cartilage, a total hip arthroplasty (THA) may be indicated.⁹

During the THA the natural articulation between the acetabulum and the femoral head is replaced by an artificial articulation between a prosthetic cup and femoral head which is connected to a stem (Fig. 1).

Preoperative planning is the first step in the whole surgical process and means that with the

use of a plain pelvic anterior-posterior (AP) x-ray image of the patient, a structured set of steps is carried out to obtain the optimal fit of the hip implants and to determine the best technique to restore the physiological anatomic relations. Preoperative planning also provides the surgeon with a tool to ascertain that the correct prosthetic component sizes are available.¹⁻³

MAGNIFICATION FACTOR CALIBRATION

Determination of the magnification factor of the projection of the hip joint on the plain pelvic AP radiograph is the first step of preoperative planning. This is done by comparing the dimensions of a fixed-reference object (in millimeter) in the x-ray image to its dimension in real life (in millimeter). The result is noted as the magnification factor (in percent) of the image. The magnification factor is crucial to obtain the correct measurement values and to determine the correct size of the implant.

At this moment, HyperOrtho™ is used for the preoperative planning in the University Medical Center Groningen (UMCG, Groningen, The Netherlands). Because the length in the digital image is measured in pixels, the magnification factor has pixels/mm unit. A femoral head implant with a known diameter of 28 mm is used as standard reference object and is placed in every plain pelvic x-ray image taken in the hospital (Fig. 2). The femoral head is usually placed between the legs of the patient at approximately the same height as the hip joint by using a height-adjustable holder. The femoral head positioning is as follows. The patient is in a supine position in the x-ray table. Both legs are internally rotated (if possible up to 15 to 20°) to neutralize the femoral anteversion. The great trochanter is palpated and a mark is set at the point where it is most clearly palpable. This is the height at which the femoral head is positioned. The calibration is performed by measuring the diameter of the object in the image (in pixels) and then by comparing it to the actual diameter (28 mm). The validity of this method is discussed by The et al.¹¹

The calibration is a time-consuming and elaborate manual process. Therefore, a (semi)automatic routine is developed.

Fig 1. Examples of implants used in THA (left) and an illustration of the insertion of the implant into the femur bone (right). (Mallory/Head® model manufactured by Biomet Inc.¹⁰).

Fig 2. Reference object's position in the x-ray image (top); reference object zoomed in (bottom, right); reference object in real-life appearance placed on a height-adjustable holder (bottom, left).

GRADIENT VECTOR FLOW SNAKE ALGORITHM FOR AUTOMATIC OBJECT DETECTION

Semiautomatic calibration requires an algorithm to automatically detect the reference object. To achieve this, the algorithm has to detect the object's boundary. Based on the detected boundary, a circle will be drawn enclosing the reference object. The diameter of the drawn circle resembles the diameter of the reference object.

The algorithm used for the automatic reference object detection is the gradient vector flow (GVF) snake. This algorithm is a modification of the traditional snake algorithm. A snake is a curve defined inside an image, which can move under influence of both internal forces within the snake itself as well as external forces derived from the image data. Those forces are defined in such way that the snake will conform to an object boundary. A traditional snake is defined as $\mathbf{v}(s) = [x(s), y(s)]$,

where $s \in [0, 1]$. The snake moves through the spatial domain of an image to minimize the energy function:

$$E = \int_0^1 (E_{int}(\mathbf{v}(s)) + E_{ext}(\mathbf{v}(s))) \quad (1)$$

The internal energy can be written as:

$$E_{int} = \alpha(s)[\mathbf{v}'(s)]^2 + \beta(s)[\mathbf{v}''(s)]^2, \quad (2)$$

where α and β are weighting parameters that control the snake's elasticity and rigidity, respectively.

In a typical application using gray-scale images, the traditional snake uses the image gradient function to express the external energy:

$$E_{ext} = -|\nabla I(x, y)|^2, \quad (3)$$

where $I(x, y)$ is the image function.

A snake that minimizes E in equation (1) must satisfy the Euler equation:

$$\alpha \mathbf{v}''(s) + \beta \mathbf{v}''''(s) - \nabla E_{ext} = 0 \quad (4)$$

To solve equation (4), the snake is made dynamic by treating $\mathbf{v}$ as a function of time as well as of s —i.e., $\mathbf{v}(s, t)$. The partial derivative of $\mathbf{v}$ with respect to t is set equal to the left-hand side of equation (4) as follows:

$$\mathbf{v}_t(s, t) = \alpha \mathbf{v}''(s, t) + \beta \mathbf{v}''''(s, t) - \nabla E_{ext} \quad (5)$$

When the solution of $\mathbf{v}(s, t)$ stabilizes, the term $\mathbf{v}_t$ vanishes and the solution for equation (4) is achieved. Solution for equation (5) can be found by making the equation discrete and solving the discrete system iteratively.⁸

The traditional snake has one main weakness: it has a relatively small capture range. The GVF algorithm is a modification of the traditional snake developed to overcome this weakness. The gradient vector flow is actually an external force field made to replace the external force term in equation (4), which is $-\nabla E_{ext}$. The GVF is defined as a vector field $\mathbf{g}(x, y) = (u(x, y), v(x, y))$. Thus, the energy function becomes:

$$\mathbf{v}_t(s, t) = \alpha \mathbf{v}''(s, t) + \beta \mathbf{v}''''(s, t) + \mathbf{g} \quad (6)$$

First, an edge map of the image ($f(x, y)$) is needed to make a GVF field. The edge map is derived from the image data and has larger values

near the edges. Usually, a gradient image is sufficient for an edge map. The GVF is a force field that minimizes the energy function:

$$\varepsilon = \iint \left(\mu (u_x^2 + u_y^2 + v_x^2 + v_y^2) + |\nabla f|^2 |\mathbf{g} - \nabla f|^2 \right) dx dy \quad (7)$$

The GVF can be found by solving the following Euler equation:

$$\mu \nabla^2 u - (u - f_x) (f_x^2 + f_y^2) = 0 \quad (8a)$$

$$\mu \nabla^2 v - (v - f_y) (f_x^2 + f_y^2) = 0 \quad (8b)$$

A solution to equations (8a) and (8b) can be obtained by treating u and v as function of time and solving:

$$\begin{aligned} u_t &= \mu \nabla^2 u(x, y, t) \\ &\quad - (u(x, y, t) - f_x(x, y)) (f_x^2(x, y) + f_y^2(x, y)) \end{aligned} \quad (9a)$$

$$\begin{aligned} v_t &= \mu \nabla^2 v(x, y, t) \\ &\quad - (v(x, y, t) - f_y(x, y)) (f_x^2(x, y) + f_y^2(x, y)) \end{aligned} \quad (9b)$$

The steady state solution (as $t \rightarrow \infty$) of these Euler equations (9a) and (9b) is the desired solution.

AUTOMATIC CALIBRATION ALGORITHM

There are four main steps in performing the automatic calibration in the software, i.e.:

1. Manually locating the reference object (single click)
2. Rough detection of the reference object's boundary
3. Detection of the reference object's boundary using the GVF snake algorithm
4. Drawing the enclosing circle

The first step is a manual indication of the position of the reference object in the image by clicking near its center (Fig. 3a). This still needs to be done manually, as the location of the reference object in the image and the orientation of the image are not fixed.

In the second step, the boundary of the reference object is roughly detected. In this way, the reference object is isolated to be able to construct the initial snake for which the gradient data from the original image are used. Starting from the user-defined point (approximately the center of the reference object), the software detects the object's boundary in eight directions: $0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ, 315^\circ$ (Fig. 3b). The detection is based on the gradient value of each pixel on the detection direction. Each pixel is scanned in the eight directions above starting from the center point. If the value of a certain pixel exceeds the threshold, it is stated as the boundary in that direction. Based on the acquired boundary points, a rectangular region of interest (ROI) is defined (Fig. 4a). Part of the image that is in the ROI is zoomed in (Fig. 4b). Also based on these coarse boundary points and prior knowledge of the circular shape of the object, a circular initial snake is placed on the zoomed area of the image.

The third step is to detect the boundary of the reference object using the GVF snake algorithm (Fig. 5a). The process is divided into two parts, based on the size of the processed image. The image is scaled down to reduce the computation load of the software. After scaling, the largest side of the rectangle will be 100 pixels. The first step processes the scaled-down image. In the second step, the larger image is processed.

Each step of object detection using the snake algorithm consists of two main tasks, ie, generating the GVF field and deforming the snake. Both tasks are iterative. The larger the image processed, the longer the processing will take. Dividing the snake detection process into two steps can decrease processing time. First, the snake is deformed to roughly match the object's boundary because the source image's resolution is low (due to downscaling). Consequently, the number of iterations (and thus processing time) in the second step can be reduced, especially in the snake deforming step because the snake is already near the intended boundary.

Another reason for dividing the process into two parts is the fact that the capture range of the object boundary is relatively small. Although the gradient vector flow has increased the capture range significantly, it still has its limitations. In the first step (using the downscaled image), the capture range can reach almost the complete image.

Fig 3. (a) First step of automatic calibration: clicking the reference object (b) Second step: reference object's rough detection in eight directions (right).

Therefore, by performing at least 100 iterations, the snake should have roughly reached the object's boundary. The boundary detection is refined by the second process using the higher detailed image.

The final step of the automatic calibration is to generate the enclosing circle. The circle is constructed using the detected boundary points from the previous step. The diameter of the circle is defined as the distance between two points of the boundary points that cover the largest distance.

The center point of the circle is defined as the middle point of the diameter line. By assuming that all snake points are already at reference object boundary, the largest distance between those points represents the object's diameter. The final circle is then drawn on the image, enclosing the reference object (Fig. 5b).

After the diameter size of the reference object is known, its real value is entered by the user. The standard value is 28 mm. However, there is a

Fig 4. (a) ROI formed based on roughly detected object's edges (b) ROI of the main image zoomed in.

Fig 5. (a) Object's boundary detection using snake algorithm (b) Final circle drawn on top of the reference object enclosing it.

possibility to enter a different value just in case another reference object is used. After that, the calibration value of the image is updated.

EXPERIMENT AND DISCUSSION

An experiment is conducted to validate the developed automatic calibration algorithm. In this experiment, the automatic and the original manual calibration are performed by three test users. The original manual calibration method is chosen to be the reference.

The experiment is performed by three different users, who will measure two pelvic AP x-ray images multiple times (ranging from 10 to 14 times on each test object). Both of the images are analog x-ray films scanned into digital images with 300 dpi resolution (0.0847 mm/pixel). These two images preference were based that they covered the two possible scenarios when pelvic AP x-ray is made for total hip arthroplasty planning purpose. The patient represented in the first image does not have a hip implant. Therefore, the test object is the nonimplanted prosthetic femoral head (marked as number 1 in Fig. 6a). The patient represented in the second image has

an implanted total hip prosthesis on the right side. Therefore, this image contains two objects to be measured, namely the nonimplanted prosthetic femoral head (marked as number 2 in Fig. 6b) and the femoral head that is in situ as part of a total hip replacement (this object is referred to femoral head implant for ease of later explanation and marked as number 3 in Fig. 6b).

The test results (Table 1) show that the mean outcome of automatic and manual calibration is similar. The relative difference of automatic calibration compared to manual calibration is calculated by equation (10). Overall, the average relative difference between them is about 1%.

$$Difference = \frac{automatic - manual}{manual} * 100\% \quad (10)$$

Furthermore, the calibration result from the automatic calibrations tends to be more precise than the result from manual calibration. The maximal standard deviation obtained from automatic calibration is 0.00068 mm/pixel, which corresponds to 0.8% in magnification factor. Although this number may look small, it is not insignificant since a 3–4% difference in magnification factor will cause one size different in

Fig 6. Objects used as test subjects in experiment.

cup size (for example from cup 54 to 56). In eight out of nine pairs of automatic and manual calibration, the automatic calibration has a smaller standard deviation than the manual one. Only in one pair of automatic and manual calibration the automatic calibration has a larger standard deviation.

In some cases, the automatic calibration fails. This was the case occasionally with the first image. From the test results of users 1 and 2, each experiment produced four failed results from total 14 experiments. The cause of this failure might be a high-density object (high gradient) other than the reference object. A text containing patient's identity exists at the bottom of the image. However, to

protect patient's identity, the text is covered by a black bar (see Fig. 6). The main principle of the snake algorithm is that the snake is attracted to the edges. If a stronger edge exists around the intended object, the snake will be attracted to that stronger edge. Therefore, objects with stronger boundaries (edges) close to the reference object (such as, in this case, the text) will attract the snake and disturb the detection of the calibration object. However, because permanent placement of the patient's name directly to the image is only done in analog x-ray image (x-ray film), this problem will be less prominent in the near future because most x-ray images used for analysis purposes will be in direct digital form.

Table 1. Experiment Result

Observer	Image	Object	Result (mm/pixel) ¹		Success Rate ²	Difference ³ (%)
			Manual	Automatic		
1	1	1	0.0778 + 0.00062	0.0783 + 0.00028	10/14	0.64
	2	2	0.0842 + 0.00079	0.0848 + 0.00068	10/11	0.71
		3	0.0811 + 0.00059	0.0804 + 0.00055	12/12	-0.86
2	1	1	0.0786 + 0.0006	0.0781 + 0.0004	10/14	-0.64
	2	2	0.0835 + 0.00041	0.0845 + 0.00055	10/10	1.20
		3	0.0805 + 0.00105	0.0804 + 0.00049	10/10	-0.12
3	1	1	0.0778 + 0.00068	0.0784 + 0.00047	10/10	0.77
	2	2	0.0836 + 0.00044	0.085 + 0.00035	10/10	1.67
		3	0.0812 + 0.00091	0.0803 + 0.00054	10/10	-1.11

¹The result is presented in mean + standard deviation

²The numbers presented indicate the amount of success attempts/total attempts

³The number presented indicate quantitative difference between automatic and manual result (difference = (automatic-manual)/manual × 100%).

The total time required for each automatic calibration is approximately 4–5 s. The total time for each manual calibration is user dependent. The experienced user took about 10 s for one calibration; meanwhile, the less experienced user took about 10–15 s. The total amount of user interference has been reduced significantly. Only one user input is required in the beginning of the process, namely, the location of the reference object (single click).

CONCLUSION

The process of calibrating the magnification factor of a hip x-ray image has been made semiautomatic by applying GVF snake algorithm to detect the reference object. The manual user interference has been reduced significantly. Therefore, the process has become more user-friendly. Furthermore, the experiment has shown that the results of the automatic calibration closely match the results of the manual calibration. Therefore, it is concluded that this algorithm can be used to perform calibration for THA planning.

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