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Parametric model of human body shape and ligaments for patient-specific epidural simulation

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ABSTRACT

Objective: This work is to build upon the concept of matching a person's weight, height and age to their overall body shape to create an adjustable three-dimensional model. A versatile and accurate predictor of body size and shape and ligament thickness is required to improve simulation for medical procedures. A model which is adjustable for any size, shape, body mass, age or height would provide ability to simulate procedures on patients of various body compositions.
Methods: Three methods are provided for estimating body circumferences and ligament thicknesses for each patient. The first method is using empirical relations from body shape and size. The second method is to load a dataset from a magnetic resonance imaging (MRI) scan or ultrasound scan containing accurate ligament measurements. The third method is a developed artificial neural network (ANN) which uses MRI dataset as a training set and improves accuracy using error back-propagation, which learns to increase accuracy as more patient data is added. The ANN is trained and tested with clinical data from 23,088 patients.
Results: The ANN can predict subscapular skinfold thickness within 3.54 mm, waist circumference 3.92 cm, thigh circumference 2.00 cm, arm circumference 1.21 cm, calf circumference 1.40 cm, triceps skinfold thickness 3.43 mm. Alternative regression analysis method gave overall slightly less accurate predictions for subscapular skinfold thickness within 3.75 mm, waist circumference 3.84 cm, thigh circumference 2.16 cm, arm circumference 1.34 cm, calf circumference 1.46 cm, triceps skinfold thickness 3.89 mm. These calculations are used to display a 3D graphics model of the patient's body shape using OpenGL and adjusted by 3D mesh deformations.
Conclusions: A patient-specific epidural simulator is presented using the developed body shape model, able to simulate needle insertion procedures on a 3D model of any patient size and shape. The developed ANN gave the most accurate results for body shape, size and ligament thickness. The resulting simulator offers the experience of simulating needle insertions accurately whilst allowing for variation in patient body mass, height or age.

1. Introduction

The patient's body shape makes a difference to the way medical procedures are performed. Medical simulators have become increasingly popular in recent years. Anatomical 3D models have been incorporated into practice for various procedures such as epidural needle insertion, surgical techniques such as laparoscopy, dentistry, and urethral catheterization. Medical simulators often contain a manikin on which the procedure is performed which generally represents an average body mass but does not change for patients of different size. The procedures can be performed the same way each time which does not encapsulate procedural variation due to varying body mass of patients.

In reality, there is a great deal of variations between different patients' sizes and body shapes; a point that has become ever so more prominent due to the recent obesity epidemic. These patient variations greatly affect many anaesthetic and surgical procedures, such as epidural needle insertion for which a longer Tuohy needle may be required for the morbidly obese to traverse additional adipose tissue. Anaesthetists find that successful insertion of an epidural catheter is much harder in overweight and obese parturients due to difficulties in locating the midline of the spine during palpation [1–3]. The Mediseus epidural simulator attempted to

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encapsulate patient variety with two options for obese or normal size, but recent studies suggest that is not enough to represent the continuous nature of patient variation [4]. Modelling for a patient's body mass index (BMI) is important since obesity is rising to an epidemic level and the Health Survey for England (HSE) showed that in England 26.1% of all adults were obese in 2010. To address these issues, an adaptable human body shape model is required. A model which is adjustable for any size, shape, body mass, age or height would provide ability to simulate procedures on patients of various body compositions.

Previous related studies include an isomorphic polygon model for describing human body shape [5]. A relationship between BMI and waist-to-hip ratio (WHR) was proposed [6]. Research into modelled clothing has stretched garments to fit onto 3D human models of various body shapes using skeleton-driven volumetric deformation [7]. Moreover, body water volume (BWV) has been estimated from anthropometric measurements [8–10]. Measurements of the human body are often taken by clinicians to provide information on body composition by analysing various metrics. These include circumferences of waist, thighs, hips, BMI derived from body mass and height, WHR or BWV [11]. Body shape descriptors such as apple, pear, hourglass and banana are often used to describe the visual shape caused by varying proportions of the patient's musculoskeletal configuration. All of these are useful to determine various aspects of body composition. Also gender should be taken as an input to a body shape model because males and females with equal weight and height may have different average body circumferences. This work aims to implement such a body shape model.

A patient-specific epidural simulator has been created based on measurements and developed empirical relations using the body shape model, ligament thickness model for graphic visualization. This provides a patient-specific epidural simulator, able to reconstruct any body shape from patient measurements to provide a more complete scenario in which to learn and practice the epidural procedure. All information describing the shape of the patient's body and ligaments is visualized in 3D using OpenGL with a 3D mesh. Deformations are applied to the body shape mesh changing the shape to match any particular patient. The increased variation of patient-specific simulation provides a learning tool that offers a better training experience for anaesthetists. This can increase skill levels, improve progression along the learning curve, reduce the number of failed insertions and reduce the risk of harm to patients.

The presented model takes standard anthropometric patient data of body mass, height and age as inputs. Empirical formulae are then developed to calculate body circumferences, total body water (TBW), and WHR for the patient's body. A novel anatomical model of spinal ligaments in the back is then developed for epidural training. Whilst detailed models for other body parts such as pelvis are available [12], no quantitative anatomical model of the ligaments in the back exists in the literature. The ligament model can adjust in size and thickness to match any patient. This includes all layers that the epidural needle passes through during insertion such as skin, subcutaneous fat, supraspinous ligament, interspinous ligament, ligamentum flavum before finally reaching the epidural space. Layer thickness and density are important for epidural simulation because in vivo, each tissue layer causes a different level of force on the needle which is sensed by the operator. This haptic feedback helps guide the epiduralist to 'feel' the ligaments to successfully carry out the procedure.

Two main problems are tackled in this paper: (1) To generate 3D visualization of body shape to match measurements of a patient's body mass, height, body shape and age. (2) To accurately calculate thickness of modelled spinal ligaments, bone, fat and skin for patients of any size and shape. Novel aspects of this work include the 3D visualization of body shape adjustable to match any patient size and shape based on clinical metrics, the anatomical model of ligaments of the back for epidural insertion which adjust in size and shape, and the collection of clinical body shape metrics into one system. These are combined into the first patient-specific epidural insertion simulator for any body shape and size.

2. Methods

For each patient a set of standard anthropometric measurements are taken. The measurements are inputs to the mathematical model: m (body mass, kg), h (height, cm), including a (age, years) and s (sex, male/female). Also, a qualitative description of body shape (Apple, Pear, Hourglass or Banana) and number of weeks pregnant are taken if applicable. These are chosen because they are easily achievable yet descriptive anthropometric data.

Formulae are then applied to calculate the BMI, TBW, fat mass, fat-free mass and to estimate the circumferences of waist, hip, thigh, calf and arm. Thicknesses of ligaments in the back are also calculated including all layers that the epidural needle passes through. These are thickness (mm) of skin, subcutaneous fat, supraspinous ligament, interspinous ligament, ligamentum flavum and epidural space.

Finally a graphical visualization is displayed using the body shape estimations to generate a visual model matching the shape and size of the patient's body.

2.1. Body shape empirical relation formulae

BMI is a standard parameter and is calculated using the existing Eq. (1). It is notable that height has more effect on BMI than body mass. Halving body mass halves BMI whereas halving height quadruples BMI. The same BMI cut-offs are used for both men and women who have different body compositions and due to this BMI underestimates adiposity in women [13].

$$\mathrm{BMI} = \frac{m}{h^2} \tag{1}$$

where BMI—body mass index, m—body mass (kg), h—height (m).

TBW is predicted by Eq. (2) based on the female Watson formula [10]. Alternative methods do exist but are less accurate [14] such as taking 58% of the body mass, the Hume–Weyers formula [8] or the Chertow formula [15]. TBW increases linearly with height and body mass but in males decreases with age. Low TBW indicates dehydration which dries the skin and causes organs to shrink which could affect needle insertion.

$$\mathrm{TBW} = -2.097 + (0.1069\,h) + (0.2466\,m) \tag{2}$$

where TBW—total body water.

Fat mass (FM) is calculated directly from BMI by Eq. (3) which is based on [14]. Fat-free mass (FFM) is the remainder of body mass when fat mass is subtracted, given in Eq. (4). Fat mass as percentage of body mass is given by $(\mathrm{FM} \times 100/m)$. Women have larger quantities of subcutaneous fat deposits than men, and women carry subcutaneous fat in their gluteal region; men carry most of their fat in the abdominal region. In obesity, there is a higher level of ectopic fat accumulating within cells of non-adipose tissue.

$$\mathrm{FM} = (1.9337\,\mathrm{BMI}) - 26.422 \tag{3}$$

$$\mathrm{FFM} = m - \mathrm{FM} \tag{4}$$

where FM—fat mass (kg), FFM—fat free mass (kg).

Body cell mass (BCM) is given by Eq. (5), calculated from the fat-free mass [14]. BCM can be given as a percentage of body mass, by $(\mathrm{BCM} \times 100/m)$.

$$\mathrm{BCM} = (0.3655\,\mathrm{FFM}) + 4.865 \tag{5}$$

where BCM—body cell mass (kg).