COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 130 (2016) 46–53

ELSEVIER

journal homepage: www.intl.elsevierhealth.com/journals/cmpb

The evaluation of a novel haptic-enabled virtual reality approach for computer-aided cephalometry

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ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
9 March 2016
Accepted 9 March 2016

Keywords:
Cephalometry
Haptic technologies
Cephalometric values
Landmark selection
Task completion time (TCT)

ABSTRACT

Background and objective: In oral and maxillofacial surgery, conventional radiographic cephalometry is one of the standard auxiliary tools for diagnosis and surgical planning. While contemporary computer-assisted cephalometric systems and methodologies support cephalometric analysis, they tend neither to be practical nor intuitive for practitioners. This is particularly the case for 3D methods since the associated landmarking process is difficult and time consuming. In addition to this, there are no 3D cephalometry norms or standards defined; therefore new landmark selection methods are required which will help facilitate their establishment.

This paper presents and evaluates a novel haptic-enabled landmarking approach to overcome some of the difficulties and disadvantages of the current landmarking processes used in 2D and 3D cephalometry.

Method: In order to evaluate this new system's feasibility and performance, 21 dental surgeons (comprising 7 Novices, 7 Semi-experts and 7 Experts) performed a range of case studies using a haptic-enabled 2D, 2½D and 3D digital cephalometric analyses.

Results: The results compared the 2D, 2½D and 3D cephalometric values, errors and standard deviations for each case study and associated group of participants and revealed that 3D cephalometry significantly reduced landmarking errors and variability compared to 2D methods.

Conclusions: Through enhancing the process by providing a sense of touch, the haptic-enabled 3D digital cephalometric approach was found to be feasible and more intuitive than its counterparts as well effective at reducing errors, the variability of the measurements taken and associated task completion times.

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http://dx.doi.org/10.1016/j.cmpb.2016.03.014

1. Introduction

Cephalometric analysis is a standard auxiliary diagnostic tool used in oral and maxillofacial surgery. Conventionally it is performed on the 2D lateral radiograph of a patient's head. However, this only represents a composite of the patient's skull on the sagittal plane. Most patients with congenital and acquired cranio-maxillofacial deformities are asymmetric and, as a consequence, the deformity is three-dimensional [1]. Therefore, conventional 2D cephalometry is not ideal for deformity analysis, diagnosis and treatment. It is also time-consuming and with accuracy depending on the specialist's ability to locate landmarks and measure all of the cephalometric variables consistently.

Research suggests that 3D cephalometry has the potential to achieve more precise diagnosis and analysis of cranio-maxillofacial deformities over conventional 2D radiographic approaches [1–4]. Other work comparing 2D and 3D cephalometry [5–11] reports that tracing a 3D model is both difficult and time consuming as some landmarks are hard to identify on 3D models. Also, there is no standard set of cephalometric variables or standards that exist for 3D cephalometric measurement and diagnosis. Therefore, new landmark selection methods are required to both improve diagnosis and to facilitate the establishment of new reference norms and standards [12]. The literature also highlights that there is a need to improve modern computer-based interactive cephalometric system usability, user friendliness and intuitiveness to facilitate easier and more accurate 2D and 3D cephalometric analyses.

This research attempts to resolve the issue of providing effective 3D cephalometric analysis through the use of haptic technologies in order to overcome many of the difficulties and disadvantages of current landmarking methods. Using the sense of touch in this way to enhance the user experience could potentially enrich the usability and intuitiveness of cephalometric computer-based systems.

Therefore the aim of this study was to evaluate the feasibility and effectiveness of using haptics in computer-aided cephalometric analysis.

2. Related work

Key general issues associated with conventional radiographic cephalometric analysis are: (i) errors in manual methods are multi-factorial with low reproducibility; (ii) landmark accuracy is highly dependent on the analyst's experience and knowledge, a key source of error [13]; (iii) some 2D cephalometric analysis variables do not exist in 3D; (iv) 3D projections errors exist when 3D objects are projected onto 2D; (v) most patients are asymmetric and the measurements distorted in the presence of facial asymmetry [1]; and many 3D deformities are three-dimensional and unsuitable for precise 2D diagnosis and treatment [1]. It is also important to bear in mind that a cephalometric analysis and diagnosis cannot be carried out in a definitive manner; many important variables such as age, sex, type, anatomic limitations and ethnic differences are also required to be taken into account [14].

Research comparing 2D traditional (manual) cephalometry with 2D digital (computer aided) cephalometry [15–17] has shown no difference between these techniques when used to predict cephalometric values, with similar errors and low reproducibility apparent in each case. However, digital cephalometry streamlines the analysis by automatically computing the cephalometric variables, leading to a number of benefits such as reliability, repeatability, improved task completion times and greater ease of use. However, when using both methods, radiographic images generate inhomogeneous broadening and distortion of the skull side structures causing inaccurate references and, consequently, misdiagnosis [18].

To overcome the disadvantages of 2D cephalometry several studies have focused on the development and validation of 3D procedures and analysis. For example, a 3D-CT procedure to assess and diagnose patients with facial asymmetry by locating 3D reference points on a scan was proposed in [2] with results suggesting that 3D-CT has potentially powerful diagnostic capabilities; however, the high patient radiation dose associated with CT scanning limits its application. An investigation to evaluate the measurement accuracy of 3D volumetric images from spiral CT in vitro was presented in [3] which concluded that the 3D reconstructed skull and facial bone landmark measurement is quantitatively accurate for surgical planning and craniofacial fracture evaluation and treatment. The adaptation of 2D cephalometric analysis into 3D was proposed in [4]. Using ACRO 3D rendering and measurement software, 3D CT surface renderings over profile X-ray were evaluated for 26 dry skulls and the results compared with those taken on the same skulls using a 3D measuring instrument showing that the software was a reliable tool which could be used to develop effective 3D CT cephalometric analysis.

Comparative analysis research between 2D and 3D cephalometry [6–11] has been focused on cephalometric landmarking by placing repeated marks to evaluate the error between the 2D and 3D cephalometric approaches. The results suggest that measurements from conventional 2D cephalometric radiographs differ significantly from those on 3D models of the same skull since in the latter the actual anatomical geometry is measured and not just its 2D projection. Several advantages of 3D cephalometry were acknowledged: (1) the actual anatomical structures can be identified; (2) cephalometric variables can be measured in 3D; (3) projection errors are eliminated; (4) the facial asymmetry errors are eliminated; and (5) patient position and orientation in the 3D scanner is not important since the final model can be located and reoriented to any desired position or orientation. However, the drawbacks that make 3D cephalometry currently clinically unusable are: (1) the free manipulation and tracing of 3D models are difficult because orthodontics and maxillofacial surgeons are experienced in the use of 2D radiographs [5]; (2) landmarking is difficult and time consuming because inner cephalometric marks, e.g. sella, upper incisor apex, etc., are difficult to identify on 3D models, therefore CT slices have to be selected to mark their location [5]; (3) the accuracy and reproducibility of 2D cephalometry measurements is higher than for 3D measurements [5]; (4) current cephalometric analysis and variables are based on 2D projections; (5) 3D cephalometry