CLINICAL ARTICLE

Accuracy and Reliability of Computer-aided Anatomical Measurements for Vertebral Body and Disc Based on Computed Tomography Scans

Jie Yao, MM[1,2], Bo Dong, MM[1,3], Ju Sun, BS[3], Jian-tao Liu, MM[4], Fang Liu, MM[2], Xiao-wei Li, MM[2], Pu-wei Yuan, MD[2], Jian-bao Zhang, MD[1]

[1]The Key Laboratory of Biomedical Information Engineering, Ministry of Education, School of Life Science and Technology, Xi'an Jiao Tong University, Xi'an, [2]Department of Nursing, Shaanxi University of Chinese Medicine and [3]Department of Orthopaedic, Affiliated Hospital of Shaanxi University of Chinese Medicine, Xianyang and [4]Spinal Cord Surgery, People's Hospital of Henan Province, Jinshui District, Zhengzhou, China

Objective: To assess whether the computed tomography (CT)-based method of three-dimensional (3D) analysis (Mimics) was accurate and reliable for spine surgical anatomical measurements.

Methods: A total of 40 lumbar segments and 32 inter-vertebral discs from eigth adult male cadavers without fractures or deformities fixed with the classical formaldehyde method were included in this research on 5 June 2017. CT scans including seven dimensions: anterior height of the vertebral body (VBHa), middle height of the vertebral body (VBHm), posterior height of the vertebral body (VBHp), width of the upper endplate (EPWu), depth of the upper endplate (EPDu), anterior height of the inter-vertebral disc in the median sagittal plane (IDHa), and posterior height of the inter-vertebral disc in the median sagittal plane (IDHp). They were performed based on uniform conditions (slice thickness: 0.625 mm) using a CT scanner on 8 June 2017. Afterwards, the surgical anatomical measurements were conducted with a Vernier caliper on 12 June 2017. The computer-aided anatomical measurements were conducted by three investigators using Mimics 16.0 to perform 3D reconstructions of CT bone on 16 June 2017. Finally, the length and angle were measured with associated measurement tools, yielding a verified accuracy of 0.01 mm and 0.01°, respectively. Each measurement was repeated three times, and all anatomical data was analyzed using the statistical software and P-value < 0.05 was considered statistically significant.

Results: The results showed no statistically significant difference was observed between the surgical anatomical and computer-aided anatomical measurements ($P > 0.05$) for lumbar vertebra measurements, and the absolute difference between surgical and computer-aided data were all less than 1.0 mm (for the VBHa, VBHm, VBHp, EPWu, and EPDu were 0.12, 0.03, 0.03, 0.31, and 0.03 mm, respectively). Moreover, although the absolute differences of discs was larger than those of lumbar vertebras, no significant differences were detected between the computer-aided and surgical anatomical measurements for the IDHa, as well as IDHp in the vast majority of measurements ($P = 0.543$, 0.079 or 0.052 for IDHa, and $P = 0.212$, 0.133 or 0.042 for IDHp). In addition, excellent reliability correlation was observed between the measurements of each investigator, and the reliability coefficients in the intra-groups were all greater than 0.9 except for IDHp (reliability coefficient = 0.892). Additionally, the reliability coefficients were greater than 0.9 for the all between-group correlations, and a significant correlation was also observed. Furthermore, no statistically significant difference for three anatomical values was found in the computer-assisted measurements of the lumbar bone structure ($P > 0.05$). Similarly, we did not observe a statistical difference in the anatomical data of the lumbar discs from the three measures ($P > 0.05$).

Address for correspondence Jian-bao Zhang, MD, The Key Laboratory of Biomedical Information Engineering, Ministry of Education, School of Life Science and Technology, Xi'an Jiao Tong University, Xi'an, Shaanxi, China 710049 Tel: +86-13891488580; Email: zhangjb6699@163.com
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Conclusions: Computer-aided anatomical measurement for spine based on CT scans presents the high accuracy and reliability for improving spinal surgical procedures.

Key words: Anatomy; Mimics; Spine; Three-dimensional imaging; Tomography

Introduction

To our knowledge, a detailed understanding of the structures of the spine is paramount for operation, and therefore, the accurate anatomical measurements of the spine play essential roles in examining spinal injuries and surgical operations. Actually, one way to study bony anatomy for surgical technique training and testing of innovative instrumentation is only based on the cadaveric specimens; these are often limited in availability. Furthermore, in the most countries, the availability of cadaveric specimens for testing remains limited because of low donation rates[1]. Hence, the imaging quality of the pathology of the spine is important, as it determines subsequent management.

With the development of computed tomography (CT), image data at high spatial resolution is widely available in the clinic and can be utilized to support computer-aided anatomical analysis. Radiologic evaluation of traumatic spines has been a predominate analysis for various spine injuries over last few years[2]. The CT-based anatomical analysis has also revolutionized quantitative measures of the pre-operative assessment of skeletal structures, which contributes to providing elaborate surgical procedures and ensuring surgical safety[3]. Previous research measured the depth of thoracic pedicle, assessed its morphological characteristics using CT-based analysis and concluded that CT measurements were relatively reliable in intra-observation and inter-observation[4]. Similarly, Sarwahi *et al.*[5] evaluated the pre-vertebral structures associated with vertebral body based on CT-based anatomical measures and pointed out that this analysis could provide a reference to crucial structures at every level for surgeons.

Due to the development of digital orthopaedics and three-dimensional (3D) printing technology, precision medicine is receiving increased attention, resulting in surgeons receiving more requests. More interestingly, with the advantages in computer-aided anatomic analysis, a wide variety of studies have indicated that the CT-based techniques combined with 3D imaging have increasingly become inevitable approaches in the anatomical analysis of different sites. For example, Guyader *et al.* [6] found CT and cone beam computed tomography (CBCT) were the reliable imaging modalities for providing 3D reconstructions of the temporal bone. Boogert *et al.*[7] revealed that the combination of OsO4, micro-CT, and the proposed image processing algorithm provides an accurate and detailed visualization of the 3D micro-anatomy of the human inner ear. More importantly, the accuracy and reliability of linear measurements using 3D computed tomographic imaging software for Le Fort I osteotomy had been investigated[8]. Taken together, using this technology, surgeons can obtain accurate definitions of anatomical structures and design or choose suitable prostheses prior to operations, such as the navigation template, customized titanium cages, and pedicle screws, as well as collect the anatomical data of some spinal structures based on CT scans. Currently, despite a study that reported a step-by-step protocol which will allow readers to easily produce 3D reconstructions for spine[9], the accuracy and reliability of this research has not been investigated.

Additionally, Mimics software, as a powerful analytical tool has been reported to be frequently applied in processing the CT-based 3D images. Briefly, in orbital diseases, the CT images of patients were used to reconstruct a 3D model of the orbital bony cavity, orbital fat, extraocular muscle, and intraorbital optic nerve using Mimics software[10]. Mimics provided detailed quantification ossification of the posterior longitudinal ligament (OPLL) volume with minimal error of inter- and intra-observer reliability in the measurement of OPLL[11]. Weissheimer *et al.*[12] investigated the accuracy of multiple imaging software including Mimics for 3D analysis of the upper airway and found that this software exhibited high accuracy compared with others assessed. Similarly, Shin *et al.*[13] also confirmed that Mimics was reliable for the reconstruction of cadaver heart anatomical structures. Although numerous researchers have collected the anatomical data of some spinal structures based on computer-aided software, few investigations evaluated the accuracy and efficiency of the 3D visualization software program (Mimics) in an anatomical analysis until now.

In the present study, the purpose of this study was to: (i) investigate the difference between the surgical anatomical and computer-aided anatomical measurements; (ii) assess the accuracy of the computer-aided anatomical measurements; and (iii) assess the reliability of the computer-aided anatomical measurement based on CT scans to verify the utility of this technology in spinal surgery. Therefore, we conducted a comparative analysis between surgical and computer-aided anatomical measurements. Briefly, the measurement values (including the vertebral body anterior height [VBHa], the vertebral body middle height [VBHm], the vertebral body posterior height [VBHp], the width of the upper endplate [EPWu], the depth of the upper endplate [EPDu], the inter-vertebral disc anterior height [IDHa], and the inter-vertebral disc posterior height [IDHp]) from computer-aided analysis were compared with those acquired from surgical anatomical data for accuracy analysis. For reliability analysis, the reliability coefficient between surgical and computer-aided anatomical measurements was calculated. Taken together, our research will provide a basis for processing medical images and improving spinal surgical operations.

Materials and Methods

Subjects

A total of 40 lumbar segments and 32 inter-vertebral discs from cadavers without fractures or deformities fixed with the classical formaldehyde method, were obtained for free by the Department of Anatomy and Tissue Embryology of Xi'an Jiaotong University Heath Center on 5 June 2017.

The inclusion criteria were as follows: (i) eight adult males; (ii) the muscle and peripheral soft tissues of specimens were carefully removed; (iii) there was no ethnic or sex preference in choosing the sample of patients, and no history of spine disease was identified in any medical records; (iv) the ligament and the capsule of the facet joint were required to be intact, which was beneficial to maintaining the physiological curvature of the lumbar spine; and (v) a comparative study. All laboratory experiments involving human subjects complied with the standards set out by the Code of Ethics of the World Medical Association (Declaration of Helsinki) and were approved by the Ethics Committee of Xi'an Jiaotong University (No. XJTULAC2017-673).

Computerized and Manual Measurements

Then CT scans were undertaken based on uniform conditions (slice thickness: 0.625 mm) using a CT scanner (GE Medical Systems, Milwaukee, WI, USA) from the Radiology Department of the Second Affiliated Hospital of Xi'an Jiaotong University on 8 June 2017 and the corresponding scan data was burned to a CD (DVD + R, 4.7 GB) for the following analysis. The seven dimensions were measured (see details in Fig. 1) as follows:

The Anterior Height of the Vertebral Body (VBHa)

VBHa (mm) is the distance between the anterior margin of the upper endplate and the anterior margin of the lower endplate on the median sagittal plane of the vertebral body. The measurement of VBHa was conducted using the vernier calipers during surgery, as well using the length measurement tool that comes with Mimics software during computer-aided anatomical analysis. The measurement of VBHa is of guiding significance for the design and model selection of artificial vertebral body in clinic. At the same time, the artificial vertebral body with appropriate size can be selected based on the measurement data of the VBHa.

The Middle Height of the Vertebral Body (VBHm)

VBHm (mm) presents the distance between the middle of the upper endplate and the middle of the lower endplate on the median sagittal plane of the vertebral body. The surgical anatomical measurements were performed by vernier calipers, and the computer-aided anatomical measurements were conducted by using Mimics 16.0. The measurement of VBHm is of guiding significance for the design and model selection of artificial vertebral body in clinical practice, and it can provide important anatomical parameters for the design and selection of intervertebral fusion device and artificial disc in clinical practice.

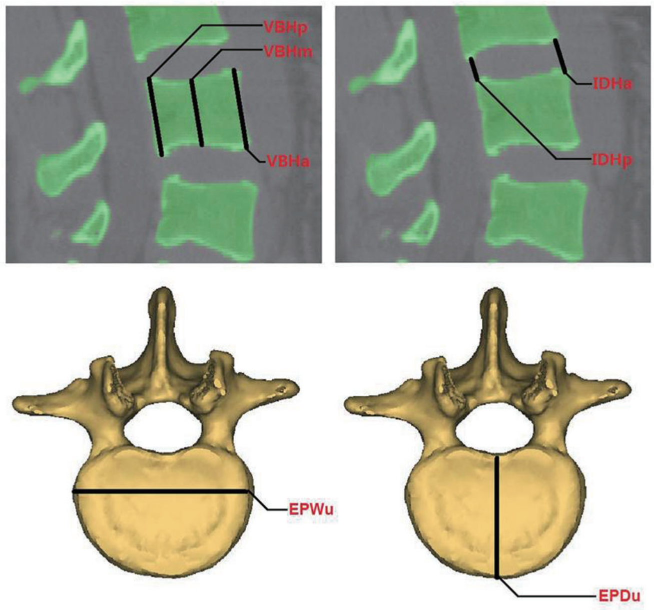

Fig. 1 The measurement indicators. VBHa, the anterior height of the vertebral body in the median sagittal plane; VBHm, the middle height of the vertebral body in the median sagittal plane; VBHp, the posterior height of the vertebral body in the median sagittal plane; IDHa, the anterior height of the inter-vertebral disc in the median sagittal plane; IDHp, the posterior height of the inter-vertebral disc in the median sagittal plane; EPWu, the width of the upper endplate; and EPDu, the depth of the upper endplate.

The Posterior Height of the Vertebral Body (VBHp)

VBHp (mm) is the distance between the posterior margin of the upper endplate and the posterior margin of the lower endplate on the median sagittal plane of the vertebral body. The surgical anatomical measurements were conducted using vernier calipers, and the computer-aided anatomical measurements were performed with the length measurement tool that comes with Mimics software. Depending on the measurement data of VBHp, the artificial vertebral body with appropriate size can be selected, thus providing important parameters for the design and selection of artificial intervertebral disc.

The Width of the Upper Endplate (EPWu)

EPWu (mm) presents the maximum width of the upper endplate on the coronal plane of the vertebral body. The measurement of EPWu was conducted using the vernier calipers during surgery, and using Mimics 16.0 during computer-aided anatomical analysis. The measurement of EPWu is helpful for the design of personalized artificial vertebral body, and has guiding significance for the model selection of artificial vertebral body.

The Depth of the Upper Endplate (EPDu)

Because the upper endplate is not a flat surface, but a concave surface in the middle. Therefore, EPDu (mm) is the shortest distance between the largest concave position of the upper endplate and the plane formed by the edge of the upper endplate. The measurement of EPDu was conducted using the vernier calipers during surgery, and using Mimics 16.0 during computer-aided anatomical analysis. The measurement of EPWu is helpful for the design of personalized artificial vertebral body, and has guiding significance for the model selection of artificial vertebral body in clinic.

The Anterior Height of the Inter-vertebral Disc in the Median Sagittal Plane (IDHa)

IDHa (mm) is the distance between the anterior margin of the disc's upper surface and the anterior margin of the disc's lower surface on the median sagittal plane of the intervertebral disc. The surgical anatomical measurements of IDHa were conducted using vernier calipers, and the computer-aided anatomical measurements were performed with the length measurement tool that comes with Mimics software. The measurement of IDHa is of guiding significance for the design and model selection of artificial vertebral body.

The Posterior Height of the Inter-vertebral Disc in the Median Sagittal Plane (IDHp)

IDHp (mm) presents the distance between the posterior margin of the disc's upper surface and the posterior margin of the disc's lower surface on the median sagittal plane of the intervertebral disc. The surgical anatomical or computer-aided anatomical measurements for IDHp were performed by vernier caliper or Mimics 16.0, respectively. The measurement data of the IDHp can provide theoretical basis for the appropriate artificial vertebral body and the design of personalized artificial vertebral body, which has guiding significance for the design of artificial vertebral body in clinic.

Afterwards, the surgical anatomical measurements were performed by an experienced investigator (Jianbao Zhang) using a vernier caliper on 12 June 2017, and the computer-aided anatomical measurements were conducted by three analyzers (Jie Yao, Ju Sun, and Jiantao); ICC value (coefficient between groups) was obtained using Mimics 16.0 (Interactive Medical Image Control System, Version 16.0, Materialize Company, Belgium) with the original threshold on 16 June 2017, which can perform 3D reconstructions of CT bone scan data (Fig. 2). Finally, the length and angle were measured with associated measurement tools, yielding a verified accuracy of 0.01 mm and 0.01°, respectively. Each measurement was repeated three times by each examiner. All authors had no access to information that could identify individual participants during or after data collection.

Statistical Analysis

All data analyses were performed with SPSS software (version 21.0, IBM Corporation, Chicago, USA) in the study were and the data were presented as the mean ± standard deviation (SD). The measurements from computer-aided analysis were compared with those acquired from surgical anatomical data using a paired sample *t*-test. The reliability coefficient was calculated for the reliability of the new measurement method. $P < 0.05$ was considered statistically significant and reliability coefficient > 0.8 indicated a better reliability.

Results

Accuracy Evaluation of the Computer-assisted Anatomical Measurements

For lumbar vertebra measurements, as shown in Table 1, no statistically significant difference was observed between the surgical anatomical and computer-aided anatomical measurements (all, $P > 0.05$). In addition, the absolute values of the differences between surgical and computer-aided data were all less than 1.0 mm, and we also found that the minimum average differences for the VBHa, VBHm, VBHp, and EPDu in terms of the median sagittal plane were 0.12, 0.03, 0.03, 0.31, and 0.03 mm, respectively. For the intervertebral discs, the absolute differences of the IDHa values (between the computer-aided measurement and the surgical anatomical measurement) acquired from three observers were 0.25, 0.74, and 0.70 mm, respectively, while the D-values for the IDHp were 0.38, 0.45, and 0.69 mm. Although the absolute differences of discs was larger than those of lumbar vertebras, no significant differences were detected between the computer-aided and surgical anatomical measurements for the IDHa and IDHp in the vast majority of measurements (all, $P > 0.05$).

Reliability Evaluation of the Computer-assisted Anatomical Measurements

To evaluate the reliability of the computer-assisted anatomical measurements, reliability coefficients were calculated between inter-groups and intra-groups (Table 2). The findings indicated that excellent reliability correlation was observed between the measurements of each investigator (Fig. 3), and the reliability coefficients in the intra-groups were all greater than 0.9 except for IDHp (reliability coefficient = 0.892). Additionally, the reliability coefficients were greater than 0.9 for the all between-group correlations, and a significant correlation was also observed (Fig. 4). Furthermore, no statistically significant difference for three anatomical values was found in the computer-assisted measurements of the lumbar bone structure (all, $P > 0.05$). Similarly, we did not observe a statistical difference in the anatomical data of the lumbar discs from three measures (all, $P > 0.05$).

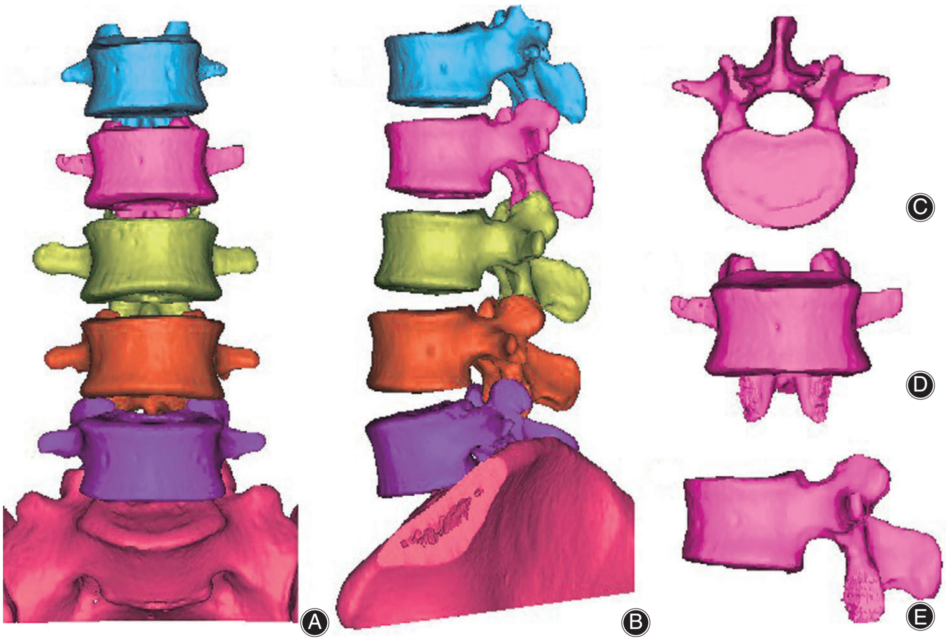

Fig. 2 CT three-dimensional reconstruction of the spine using Mimics. (A) the front view of the lumbar spine; (B) the lateral view of the lumbar spine; (C) the cranial view of a single vertebra; (D) the front view of a single vertebra; (E) the lateral view of a single vertebra.

Discussion

Computer-aided anatomical analysis has played essential roles in imaging-based digital anatomy (such as anatomical data acquisition, lesion evaluation, optimization of surgical programs, and personalized customization of prostheses) and it has been increasingly advocated for vital anatomical situations in the past few years[14–16]. Unfortunately, the vast majority of medical imaging vendors have proprietary implementations of 3D visualization that cannot be installed directly on personal computers; therefore, most

TABLE 1 Comparison between the computer-aided measurement and surgical anatomical measurement about lumbar vertebrae and intervertebral discs for 40 lumbar segments (Mean ± SD, mm)

Items	Computer-aided measurement	Surgical measurement	Absolute value of difference	*P* value
VBHa	26.49 ± 1.53[a]	26.61 ± 1.64	0.12	0.751
	27.03 ± 1.83[b]		0.42	0.281
	26.08 ± 1.46[c]		0.53	0.131
VBHm	24.88 ± 1.62[a]	25.18 ± 1.80	0.30	0.439
	25.15 ± 1.79[b]		0.03	0.949
	25.41 ± 1.87[c]		0.23	0.573
VBHp	27.95 ± 2.70[a]	27.98 ± 2.71	0.03	0.970
	28.33 ± 3.04[b]		0.35	0.588
	27.94 ± 2.68[c]		0.04	0.947
EPWu	46.31 ± 3.74[a]	45.54 ± 3.76	0.77	0.356
	45.23 ± 3.91[b]		0.31	0.719
	45.08 ± 3.70[c]		0.46	0.585
EPDu	32.46 ± 2.02[a]	32.80 ± 2.28	0.34	0.479
	32.77 ± 2.27[b]		0.03	0.952
	32.53 ± 2.02[c]		0.27	0.572
IDHa	10.04 ± 1.79[a]	10.29 ± 1.57	0.25	0.543
	9.55 ± 1.76[b]		0.74	0.079
	10.99 ± 1.19[c]		0.70	0.052
IDHp	5.37 ± 1.16[a]	5.75 ± 1.25	0.38	0.212
	5.30 ± 1.10[b]		0.45	0.133
	6.44 ± 1.39[c]		0.69	0.042

Comparison of the measurement was performed using paired sample *t*-tests. A *P*-value less than 0.05 was considered statistically significant. No significant difference was observed in the data measured by the Mimics software and surgical approach ($P > 0.05$). a, b, c represented computer-aided anatomical measurements performed by three different investigators.

TABLE 2 The reliability coefficient of the between-group and in-group computer-aided anatomical measurements

Reliability evaluation	VBHa	VBHm	VBHp	EPDu	EPWu	IDHa	IDHp
Within group							
I1	0.991	0.992	0.992	0.987	0.998	0.990	0.987
I2	0.995	0.994	0.997	0.995	0.998	0.994	0.991
I3	0.977	0.954	0.994	0.988	0.995	0.913	0.892
Between groups							
I1-I2-I3	0.975	0.990	0.993	0.989	0.975	0.965	0.976

The reliability coefficient larger than 0.8 was considered to have better reliability; The reliability coefficient larger than 0.9 and was considered to be extremely reliable. I1, I2, I3 represented different investigators who collected data using computer-aided measurement. "Within group" represented the reliability evaluation of the three measurements by the same investigator and "Between group" represented the reliability evaluation of the measurements by different investigators.

clinicians have difficulty in analyzing data directly from personal computers, which limits the role of computer-aided anatomical analysis in clinical practice. Encouragingly, the interactive medical image control system computer-aided software developed by the Materialize company (Mimics) has been reported that it could be easily installed on personal computers and perform 3D reconstruction of CT scan data[17]. Consequently, the length and angle can be measured using its associated measurement tools and yielded verified accuracies of 0.01 mm and 0.01°, respectively. And notably, overwhelming evidence has demonstrated that Mimics exerted clinically crucial roles in expanding the application of computer-aided anatomical analysis in clinical practice[13,18]. Chen *et al.*[9] reports a step-by-step protocol which will allow readers to easily produce 3D reconstructions; however, they do not test the accuracy and reliability of computer-aided anatomical measurements with 3D reconstructions for spine in practice. Here, we carried out the measurements of spine anatomy on the basis of this software and conducted a comparative analysis between surgical and computer-aided anatomical measurements. The results showed that, compared with surgical anatomical measurements, computer-aided

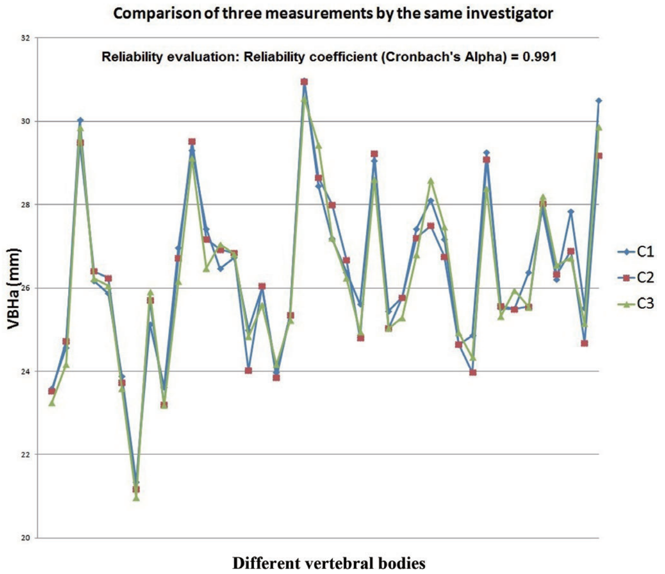

Fig. 3 Comparisons of three measurements by the same investigator. C1, C2, C3 represented different measurements by the same investigator. The image showed that the differences among the three measured data by the same investigator were small and the confidence was very good. Each point on the image represents the VBHa of each of the 40 vertebral bodies measured each time by the same investigator. VBHa: the anterior height of the vertebral body in the median sagittal plane.

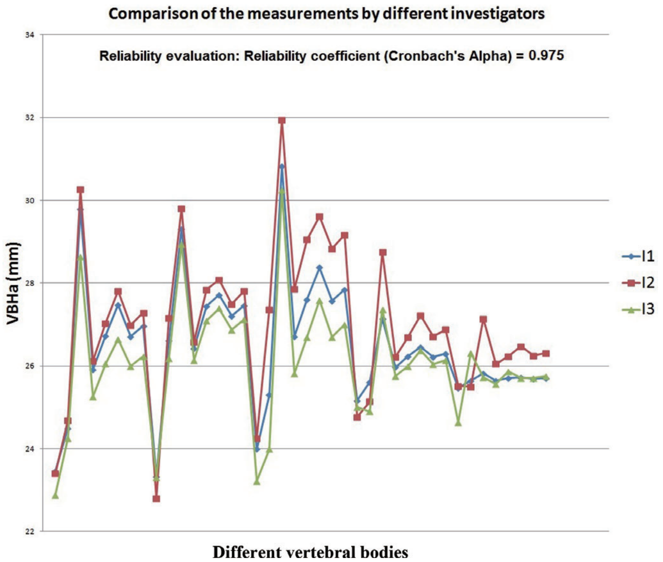

Fig. 4 Comparisons of the measurements by different investigators. I1, I2, I3 represented the measurements by three different investigators. The image showed that the differences among the three measured data by different investigators were small and the confidence was good. Each point on the image represents the VBHa of each of the 40 vertebral bodies measured each time by the different investigator. VBHa: the anterior height of the vertebral body in the median sagittal plane.

anatomical measurement for spine based on the Mimics software was highly accurate and reliable.

The Higher Accuracy of Computer-aided Anatomical Measurements for Spine

Our findings implied that no significant difference was found between computer-aided approach and traditional anatomical measurements, which was consistent with a previous study[17]. Similarly, Varghese *et al.*[19] assessed the precision of linear measurements between CT-derived images and a digital caliper and suggested that there was no statistical difference between them, which also proved the validity of computer-aided analysis. Another work compared the variability of the ossification of the posterior longitudinal ligament volume utilizing Mimics software among different observers and they pointed out that this software produced stable accuracy in measurements[20]. Moreover, we also observed that the absolute differences of the anatomical parameters obtained by the two methods was also very little (about 0.5 mm) and this small discrepancy was probably due to the thickness variation of CT scanning. Therefore, better results were obtained using ordinary CT scanning for some functions requiring less precision, such as the evaluation of a surgical lesion and the customization of prosthesis. However, it was necessary to choose ultrathin layer CT scans for 3D reconstruction and multiple measurements by multiple investigators when dealing with some demanding surgical guides and surgical puncture as well as positioning.

The Higher Reliability of Computer-aided Anatomical Measurements for Spine

Additionally, the reliability of Mimics-assisted spinal anatomical measurements were evaluated and the results indicated that there was a high correlation between the different measurements of the same investigator or the measurement data of different examiners. Furthermore, no statistically significant difference was observed between the measurements by different measurers. A previous study measured the displacement of the distal radioulnar joint and indicated Mimics 10.0 three dimensional reconstruction exhibited excellent correlation coefficient (CC) values in intra-class analyzers (ICC > 0.8), which was an acceptable reliability[21]. Wu *et al.*[22] assessed the measurements of different parameters between radiographic and 3D-printed models for spines by the intra-class correlation coefficient (ICC) analysis and argued that there was a strong resemblance (ICC values > 0.800), which was consistent with our results. Alternatively, Cossellu *et al.*[23] evaluated the intra- and inter-observer reliability of the measurements for frontal sinus based on the cone beam-CT Mimics 11.11 and found that there was no significant difference in different measurements, which revealed considerable homogeneity and high reliability and feasibility. These findings demonstrated CT-based that computer-aided measurements could support the precise anatomical analysis, which would serve as a potential option for pre-operative diagnosis and post-operative evaluation.

However, there are still some limitations in our analysis. Firstly, this study only used a 0.5 mm layer thickness for the reconstruction measurement, and the accuracy of reconstructing the scanning data for layers with different thicknesses should be further studied. In addition, the accuracy and reliability of other structures also needs to be assessed. Moreover, a comprehensive study with a larger sample size is required to verify our findings in future.

Conclusions

In conclusion, this experiment evaluated the accuracy and reliability of the Mimics computer-aided software for various anatomical parameters and the results revealed that computer-aided anatomical measurement for spine based on the Mimics software was highly accurate and reliable, which was particularly helpful in assisting clinical workers to improve the operation quality.

Acknowledgments

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