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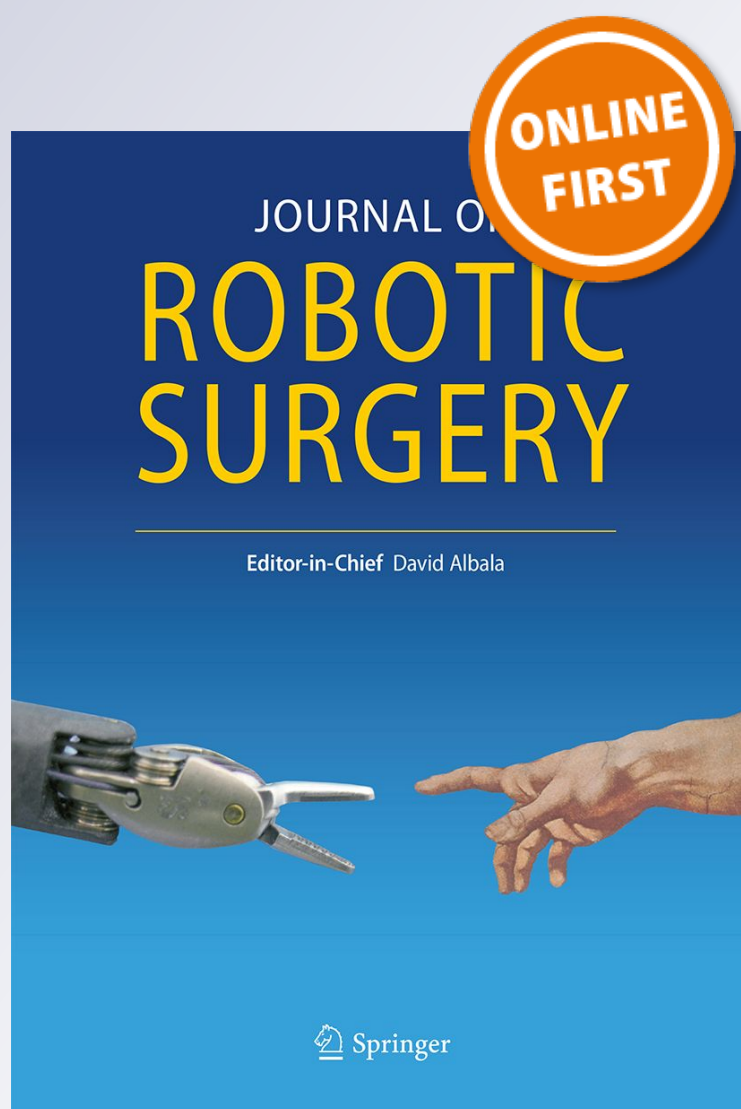
Bin Zheng, Xiaolin Wang, Yixiong Zheng & Jiexiong Feng

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3D-printed model improves clinical assessment of surgeons on anatomy

Bin Zheng[1] · Xiaolin Wang[2] · Yixiong Zheng[3] · Jiexiong Feng[2]

Abstract
Performing surgical procedures often requires a surgeon to develop a skill to create 3-dimensional (3D) mental model on patient's anatomy. Question remains whether the touching on the 3D printed model can facilitate learning of patient anatomy than viewing the rendered virtual on-screen model. The printed and the virtual 3D model were developed from CT films taken from a 4-year-old girl, who had dysplasia of the hip in the left hip. Eleven subjects were called to report measures on six key anatomical features on the hips. The reporting time and the accuracy were compared between the two models, along with the gaze characteristics of subjects while inspecting the models. The variables were analysed using a 2×2 within subject ANOVA to examine the difference between viewing the models (on-screen vs. printed-out) and the side of the hip (right vs. left). Interacting with the printed 3D model required shorter times and yielded more accurate visual judgments than viewing the virtual models on most of the anatomical features. Subjects performed a fewer number of fixations but with a longer mean fixation duration when interacting the printed than inspecting the virtual on-screen 3D model. Results confirmed the value of the printed 3D model on improving the clinical judgement on patient anatomy. Confidence in collecting information from the physical world and the cross-model sensor integration may explain why participants performed better with the printed model compared to the virtual model.

Keywords Spatial cognition · Developmental dysplasia of hip (DDH) · Anatomy inspection · Printed 3D model · Clinical skill · Surgery simulation

Introduction

Performing plastic procedures on patients requires a surgeon to develop a skill to create 3-Dimensional (3D) mental model of the patient anatomy [1, 2]. In children with limbs and joints malformation, normal human anatomy will be twisted by multiple factors, ranging from congenital defects in the skeletal and muscular system, inappropriate force on the growth plate, and secondary compensation on the nearby joints [3]. As a result, correction on the affected joint should include a compressive pre-surgery assessment by taking malformation on 3D model, rather than a 2-dimensional one. This project investigates whether a new-emerging technology, 3D printing, can help surgeons improve their 3D ability when assessing hip anatomy in children with developmental dysplasia of the hip (DDH).

DDH is a developmental deformation of the hip joint found in 0.5–20% of new-borns during routine screening [4, 5]. Given the high possibility of developing a limp and constant joint pain during the development of young children, careful developmental monitoring and early intervention are recommended [6–8]. For older children, where early non-surgical interventions are missed, peri-acetabular osteotomy (PAO) procedures can be used to realign the hip joint [8, 9]. PAO in DDH children is a complex surgical procedure that includes multiple osteotomies in the pelvic and femoral skeletal structure. To perform the PAO, pediatric orthopedic surgeons need to perform mental reconstruction on the 3-dimensional (3D) anatomy of the hip based

✉ Bin Zheng
   bin.zheng@ualberta.ca

1   Department of Surgery, Faculty of Medicine and Dentistry, University of Alberta, 162 Heritage Medical Research Centre, 8440 112 St. NW., Edmonton, AB T6G 2E1, Canada

2   Department of Paediatric Surgery, Tongji Hospital, Huazhong University of Science & Technology, Wuhan, China

3   Department of Surgery, The 2nd Affiliated Hospital of Zhejiang University, Hangzhou, China

on pre-operative medical images acquired from the patients [10–13]. This is a challenge for many junior surgeons and may be beyond skills possessed by other healthcare staff in the PAO operating team.

In most clinical practice, surgeons' knowledge about dysplasia hip is built on their review of anterior–posterior X-ray films, which they use to construct the anatomical features in their minds before entering the operating room. In the late 1980s, 3D rendering technology became available by taking data from computed tomography images. Viewing 3D images of hips on the computer screen improves surgeons' perception on patient anatomy [10, 11, 14, 15]. In 1999, Dutoit and Zambelli reported the outcome from 22 DDH cases undergoing PAO; surgeons under the guidance of 3D reconstructed images on the hips performed better in osteotomies compared to when only reviewing the image from conventional X-ray films. Patients were more satisfied with the surgical outcome where procedures were performed under 3D images guidance [16].

Entering the twenty-first century, 3D printing technology has become available in healthcare [17]. Orthopedic surgeons can actually touch the skeletal models of the patients with their hands rather than merely looking at the rendered model on the computer screens [10]. It is obvious that making a 3D printed hip model requires extra cost compared to just displaying the model on the computer screen [10]. The question we intend to ask is whether having the 3D printed model provides extra value to surgeons for better surgery compared to just looking at the virtual model on the screen.

Specifically in this project, we compared surgeons' clinical judgement on the key anatomical landmarks of the hip between inspecting the virtual on-screen 3D model and 3D printed model. A group of surgeons were asked to inspect the hip anatomy and reported their measurements (visual judgement) on the anteversion angle, neck–shaft angle, femoral head length and width and, femoral neck length and neck height between two different models (printed vs. on-screen) of the same patient. It is our hypothesis that the subjects will make better clinical judgements when touching the 3D printed model than inspecting the on-screen model.

While subjects were inspecting the hip anatomy over two different 3D models, we tracked their eye movements to reveal their eye scanning and gaze behaviours. When inspecting X-ray films, expert radiologists could detect abnormal sites [18–21] quicker and more accurate. Expert laparoscopic surgeons also displayed different scanning and gaze behaviours than novices [22–24]. We expect to record different eye scanning and gaze behaviours between the subjects interacting with the two different 3D models.

Methods

Subject and experimental environment

The study was conducted at the Surgical Simulation Research Lab at the University of Alberta. Eleven medical students (5 males and 6 females, age: 23–36, mean = 29) with normal or corrected to normal vision were included. Ethics approval was obtained from the *Health Research Ethics Board* of the University of Alberta before the recruitment of human subjects. Written consent was obtained from each participant prior to entering the study.

Task

Subjects were required to inspect a 3D model of a hip comprised of a pair of femurs at the proximal ends and report their best judgements on the measures of the neck–shaft angle, anteversion angle, femoral head length and width, femoral neck length and height (Fig. 1).

The 3D femoral model was developed based on the computed tomography data taken from a 4-year-old girl with DDH. The DDH was diagnosed on her left side while normal in the right. The computed tomography DICOM (Digital Imaging and Communications in Medicine) data were fed into 3D Slicer, a free, open source software for image visualization (http://www.slicer.org) [25], to create the on-screen femoral model, and displayed on a 24-inch high-definition PC monitor (LG-24MA31D, LG Electronics Canada Inc. North York, Ontario). The 3D rendered model was also sent to a 3D printer to create a printed model.

When subjects were inspecting the model, the order for showing the on-screen vs. the printed model and the side of hip (the left vs. the right femur) was counterbalanced among subjects. In the printed condition, the model was held in the left hand of the subject (Fig. 2a). Subjects were instructed to maintain the arms straight while resting their heads on the chin support, so that distance between head and the model was kept equal as they watched the model displayed on the monitor (Fig. 2b). Subjects were allowed to make rotations in both 3D models; the rotation of the virtual on-screen model could also be made by moving the mouse. Subjects were not allowed to zoom in/out to the virtual model; neither were they allowed to use any rulers to help in making visual judgements on the anatomy. At the end of study, subjects were asked for their comments on which model they trusted more and the reasons for them to base this trust on.

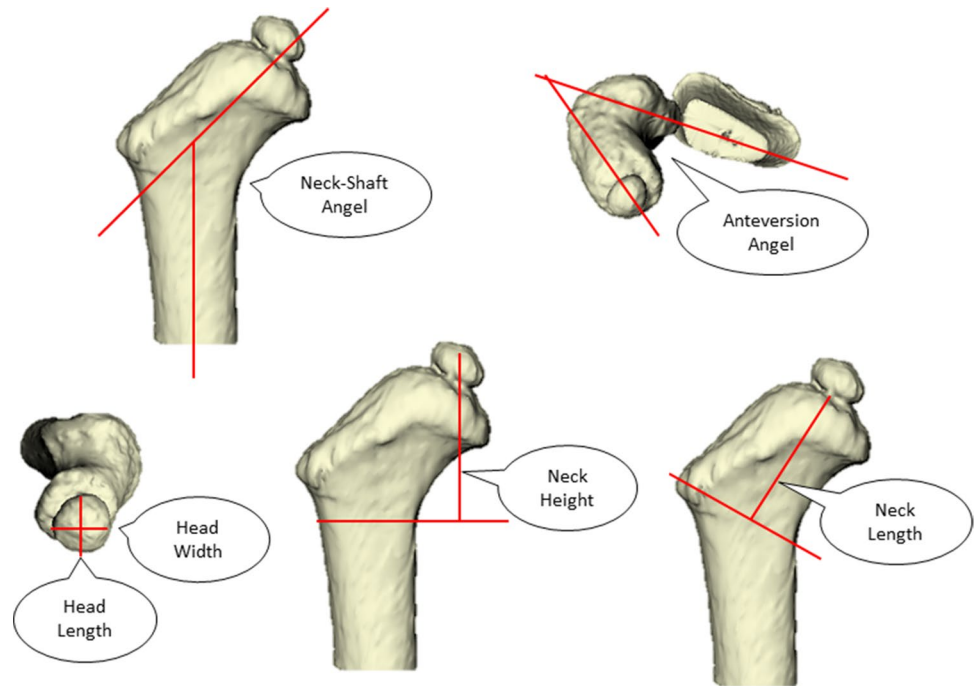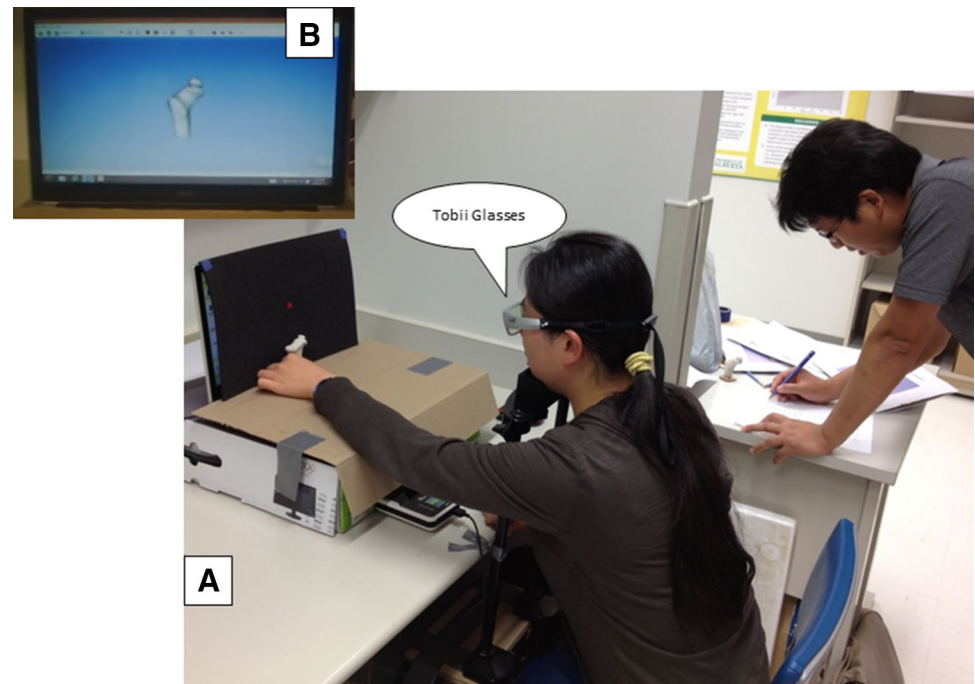**Fig. 1** Femoral parameters the subjects need to estimate

Fig. 2 Experimental setting. **a** Subject is holding the printed femoral model in hand; **b** the same virtual model is displayed on the screen. Tobii Glasses were worn by the subject to record her eye metrics during the trial

Eye tracker

A mobile eye tracker, Tobii Glasses (Tobii Technology, Danderyd, Sweden) was used to capture the subjects' eye movements while inspecting the 3D models. The Tobii Glasses record motions from the right eye at 30 Hz and is accurate to within 1 degree of the visual field. Combined with Tobii's Studio eye-tracking analysis software suite, high-definition 3-dimensional eye motion data can be obtained for further analysis.

Measures and statistics

The true values of the six parameters of the femurs were measured before the trial. Each subject's reported data were compared (subtracted) to the true values. The resultant *constant errors* were reported either in positive (where they were over-estimated) or negative (under-estimated) values. The duration each subject took to report the individual parameters was also calculated (*Judgement time* in second), starting from when the model was displayed on the screen or held in the hand to the moment when the subject verbally stated the data to the experimenter.

While subjects were visually scanning the 3D models, the Tobii glasses captured their eye motions. From Tobii Studio, we obtained data on gaze fixation. In this project, we reported *fixation counts* and mean *fixation duration* (msec) for each subject for each of the six anatomical features, which roughly describes how subjects were searching for visual inputs while making the visual judgement.

The constant error and fixation variables were analysed using a 2×2 within subject ANOVA to examine the difference between the two different viewing models (on-screen vs. printed) and side of the hip (abnormal left vs. normal right). The statistical analyses were performed using SPSS (Version 17.0, SPSS Inc., Chicago, IL, USA). A *p* value less than 0.05 was considered significant. The results are reported in this paper as mean ± standard deviation unless stated otherwise.

Results

The judgements of the subjects on the printed and the on-screen 3D models are summarized in Table 1 below. Time required for estimating femur parameters was shorter while inspecting the printed than the on-screen model. Inspecting the printed 3D model yielded more accurate visual judgments than the virtual model on most of the anatomical features (Table 1). The visualization of constant errors is displayed on Fig. 3. There was no difference between inspecting the abnormal left and the normal right side of the femoral models. There is no interaction effect on the constant errors between type of 3D model and the side of the hip.

When inspecting the printed 3D model, subjects performed fewer numbers of fixations but had longer fixation durations (Table 1). Analysis on gaze behaviours did not reveal any differences between inspecting the abnormal left and the normal right side of the femoral models. There is no interaction effect on the gaze behaviours between the type of 3D model and the side of the hip.

Discussion

Our results supported our hypothesis. Holding the printed 3D model yielded more accurate visual judgments than inspecting on the virtual on-screen model. Subjects commented

Table 1 Judgement performance between the printed and the virtual on-screen 3D model

|	Anteversion angle (°)	Neck–shaft angle (°)	Head length (mm)	Head width (mm)	Neck length (mm)	Neck height (mm)
Judgement Time (s)						
Printed	9.35 ± 6.7	10.4 ± 5.4	8.2 ± 5.2	7.4 ± 5.2	12.0 ± 3.7	11.2 ± 6.1
On-screen	16.7 ± 8.9	18.5 ± 10.9	13.1 ± 7.6	9.4 ± 5.7	15.4 ± 7.0	21.1 ± 9.4
P value	0.036	0.018	0.034	0.363	0.150	0.008
Constant Errors						
Printed	0.6 ± 3.2	1.0 ± 4.9	0.0 ± 3.2	− 1.3 ± 1.5	2.2 ± 4.6	− 2.0 ± 3.7
On-screen	− 5.1 ± 10.6	− 4.7 ± 14.3	5.1 ± 6.1	3.7 ± 5.4	9.2 ± 6.2	3.1 ± 10.3
P value	0.064	0.047	0.004	0.001	0.001	0.089
Fixation Count						
Printed	19 ± 12	25 ± 11	25 ± 14	16 ± 9	28 ± 10	24 ± 10
On-screen	46 ± 22	43 ± 19	39 ± 17	26 ± 13	43 ± 18	43 ± 13
P value	0.001	0.008	0.008	0.059	0.012	0.000
Fixation Duration (ms)						
Printed	481 ± 176	416 ± 176	301 ± 96	361 ± 169	417 ± 177	426 ± 217
On-screen	352 ± 120	392 ± 155	262 ± 76	296 ± 114	336 ± 173	416 ± 151
P value	**0.036**	0.749	0.208	0.305	**0.024**	0.884
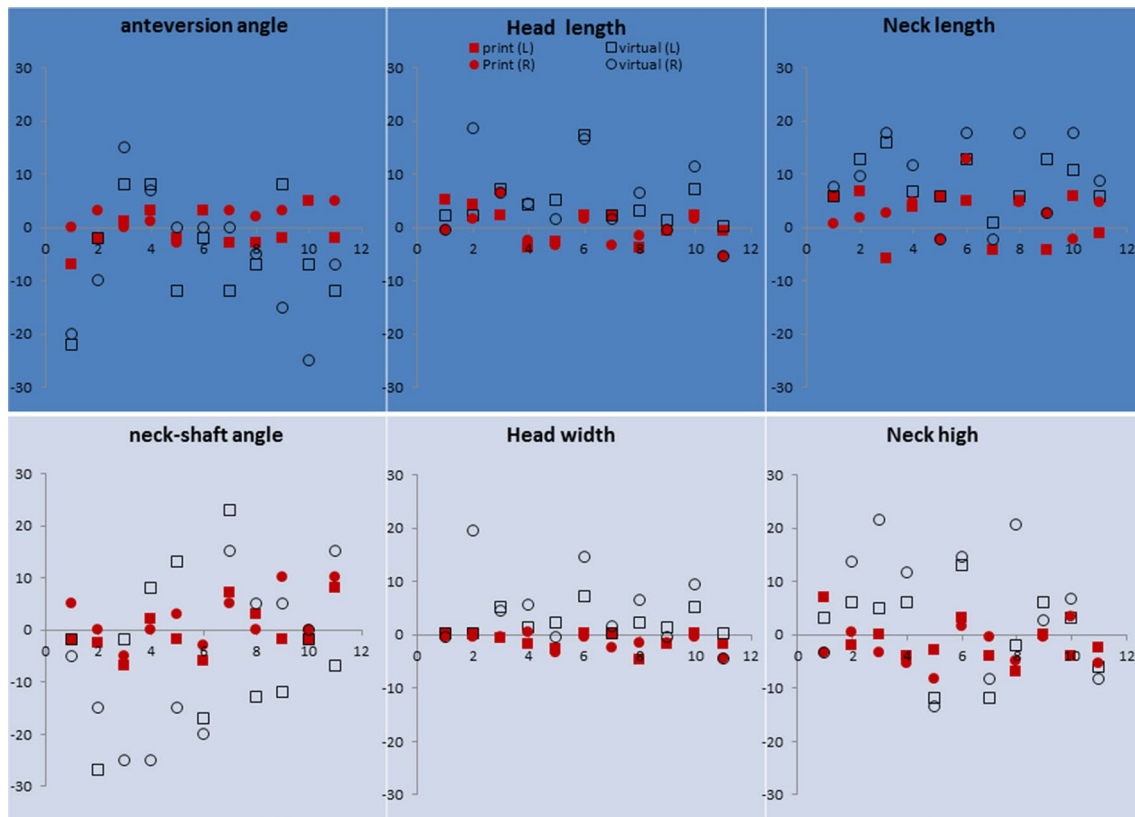
Fig. 3 Constant errors. Errors recorded while inspecting the printed model (in solid red) are distributed alone the zero line, contrasting errors recorded while inspecting the virtual on-screen model (blank circles and square)

that it was easier for them to assess the anatomy when they can see a physical 3D model in front of them. They trust the physical model more than the virtual model. Even though they had been told the model displayed on screen were at a 1:1 ratio with the real anatomy, they still hesitated to subject themselves to completely trusting the virtual model. Some commented that the resolution on each computer monitor may vary, which can alter the image in certain ways that may reduce their trust of the virtual model.

Evidence collected from eye-tracking support that human subjects perform fewer and longer fixations when inspecting the printed than the virtual model. Fixation data often been used to describe visual attention of an observer. It seems human subjects are able to focus on the printed models better than the virtual on-screen ones. When performing a demanding task, human performers gaze on the target longer before executing an action. In our cases of reviewing the printed model, the longer fixation may enrich visual intake at the critical anatomic spots, which may partially account for why subjects displayed better judgement when inspecting the printed than the virtual on-screen model.

Some people commented that they prefer holding the model in their hands as the proprioceptive feedback from hands can facilitate clinical judgment. By adding haptic/ touching feedback to the visual feedback, human operators can perform significantly better in judging the shape of objects in both real and virtual environments [26–28]. More recent studies have found support for the cross-model interaction between the visual and haptic feedback loop, which suggest human users trust information presented through the multiple sensory feedback more than when presented through only the visual channel, such as from screen based or the virtual world [29, 30]. Cross-model interaction between visual and haptic feedback loops have been found from neurological and behavioural studies [29, 30]. The virtual model suspends the pathway for humans to collect information from their hands, which may be a secondary reason of why people make worse judgements when inspecting the virtual on-screen model when compared with the printed model.

Having considered all these factors, we would like to endorse the value of making 3D printed models for enhancing simulation-based education program for training skills which requires multiple channels of sensory feedback, such as performing a surgical procedure. Having a 3D model in the hands of the young surgeon will facilitate their clinical judgement on the surgical anatomy. If possible, pre-surgical planning and rehearsal should be

performed over the 3D printed model rather than only using virtual models.

We did not find any differences between inspecting the two different sides of the hip: one normal and the other abnormal. It seems the abnormality of the hip due to the DDH did not make our subjects display distinguishable behaviours while inspecting the models. We are not sure whether experienced pediatric orthopedic surgeons will perform differently than our subjects (undergraduate medical students). This can be an interesting point to pursue when we conduct the follow-up study.

In conclusion, results collected from controlled laboratory study endorsed the value of using printed 3D model over the virtual model on improving the clinical judgement of human subjects. Confidence in the information collected from the physical world and the cross-model sensor integration may account for such a result favouring the printed model in visual detection tasks. Further studies will be needed to examine how experienced surgeons may respond differently from novices while using the printed model for surgical planning.

Compliance with ethical standards

Ethics approval Ethics approval was obtained from the *Health Research Ethics Board* of the University of Alberta before the recruitment of human subjects. Written consent was obtained from each participant prior to entering the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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