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THE DEVELOPMENT AND IMPLEMENTATION OF A HIGH-FIDELITY THREE-DIMENSIONAL PRINTED SIMULATOR FOR HIP ARTHROSCOPIC TRAINING: INSIGHTS FROM A CROSS-DISCIPLINARY

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ABSTRACT
Hip arthroscopy is an ideal technique to treat many intra-articular conditions of hip, such as femoroacebuar impingement (FAI) and labral tears. However, hip arthroscopy has its unique challenges in training and operation. Currently, the essential skills and preferred training method for hip arthroscopy remains unknown. In this study, we investigated the required surgical skills and suitable simulation method for hip arthroscopy. Based on that, a high-fidelity medical simulator would be designed.
A nation-wide online survey was carried out, which was focusing on skills that trainee should possess prior to performing hip arthroscopy in operating room. Meanwhile, the usefulness of different types of simulation had been identified. The high-fidelity simulator was developed based on medical imaging and three-dimensional (3D) printing technology. The feasibility of the simulator was evaluated based on a cross-sectional study.
The skills related to cognitive ability the treatment of FAI are the most essential for hip arthroscopic training. Cadaveric specimens are the most favorable simulation method, high-fidelity physical simulators are the preferred alternatives. A 3D printed simulator for hip arthroscopic training has been developed based on the results of the survey study, which is suitable for surgeons to practice the specific skills.
Based on the collaboration between designers and medical professionals, the effective simulation tools and training program can be developed. It is beneficial for medical trainees and the quality of healthcare.

Keywords: Cross-disciplinary Design, Survey Study, Feasibility Study, Medical Simulation Design, 3D Printing

1 INTRODUCTION

Hip arthroscopy, a minimally invasive surgical technique, has become a cornerstone in orthopaedics for treating conditions such as labral tears, chondral defects, ligamentum teres lesions, and femoroacetabular impingement (FAI)[1],[2]. Due to the minimum damage for patients, relatively less blood loss, and fast postoperative recovery, it becomes increasingly popular around the world. However, this procedure presents unique challenges due to reduced tactile feedback, a restricted field of vision, limited instrument freedom, and the need to interpret two-dimensional (2D) screen information into a comprehensive three-dimensional (3D) spatial understanding [3],[4],[5]. Orthopaedic trainees and surgeons must invest considerably more time practicing technical skills to achieve competency in hip arthroscopy. They also face challenges like ensuring safe access to anatomical locations and managing surgical time constraints, which are crucial to minimizing the risk of iatrogenic injury. These factors collectively heighten the learning difficulties associated with this specialized procedure [6].
Simulation-based training has emerged as a vital tool for bridging the gap between the surgical skills required for successful clinical outcomes and those attained by less-skilled surgeons, allowing trainees to practice and objectively evaluate their skills [7],[8]. The integration of 3D printing enhances this training by creating models with precise anatomical structures that provide tactile

feedback, particularly benefiting hip arthroscopic training [9],[10]. Research indicates that surgeons may need to perform over a hundred hip arthroscopies for optimal outcomes [11],[12], but simulation technology streamlines this learning curve by enabling safe, repeated practice rather than relying solely on operating room experience [13],[14]. Various simulators boost training efficiency, reducing the time to proficiency without compromising patient care [15],[16],[17]. This approach not only enhances technical skills in a risk-free environment but also shifts surgical education from traditional models to a more structured pathway, improving both training duration and intraoperative learning. However, surgeons' particular needs to practice hip arthroscopic skills through the simulated training has rarely been investigated. Consequently, it is difficult for medical educators and researchers to design the effective training program for surgeons to practice the specific skills.

In this study, we aimed to investigate the particular needs of hip arthroscopic training from the perspective of surgeons. Following that, based on the medical imaging and 3D printing technologies, the high-fidelity medical simulator would be developed to meet the requirements of skill training.

2 METHODS

2.1 Training surgical skills on hip arthroscopy by simulation

A nationwide online survey was conducted, the invitation to participate was posted in three social media groups organized by the Chinese Medical Association for specialists in Lower Limb Sports Medicine. It included a brief introduction and a link to the survey, which was developed on www.wenjuan.com and contained 42 questions adapted from Safir et al[18]. The questions were modified by three surgeons with at least five years of hip arthroscopy experience.

At the beginning of the survey, surgeons provided background information on their training and arthroscopic experience. Following that, they ranked the importance of surgical skills for hip arthroscopy on a 5-point Likert scale. For analysis purposes, the skills were divided into three categories: (1) identification of structures and navigation of the arthroscope, (2) instrument handling, and (3) preparation of the patient and instruments. Finally, participants rated the different types of simulation based on their usefulness in training hip arthroscopic skills.

2.2 Development and validation of the three-dimensional (3d) printed simulator

The simulator was developed using CT scans to create a 3D model of a hip joint from a 31-year-old female volunteer. Key angles of the hip were measured, and the CT data was processed with InVesalius to generate a 3D volumetric model, which was then refined in Meshmixer for 3D segmentation. The cleaned CAD file was imported into Rhino to design a modular simulator, featuring separate components that allowing for the simulation of various hip conditions. To ensure the cost-effectiveness of this simulator, the design team, in consultation with surgical experts, focused on incorporating only the key anatomical structures relevant to the procedure: the anterior superior iliac spine, acetabulum, and femur.

The hip joint capsule was shaped to accommodate traction forces, and anatomical markings were added for reference. The box-shaped simulator was designed based on a modular concept and comprised two main parts, one soft component to simulate soft tissues, the other hard component for conciseness to simulate the bony structures (Figure 1). Since surgeons typically determine the surgical site through palpation, which helps identify the anterior superior iliac spine and the greater trochanter of the femur, the external surface of the soft component was simplified to a geometric shape, as it is not critical for the design. However, the internal structure of the soft component was meticulously crafted to align with the contours of the bony structures, ensuring that the palpation feedback on the simulator closely resembles that of real patients. To replicate the tactile sensation of human tissue, the soft component was made from silicone material. After extensive testing, the Smooth-on Ecoflex 00-30 material was selected due to its close resemblance to real human tissue.

The skills of using fluoroscopy during hip arthroscopic surgery is important, that requires the bony structures of the simulator are visible under X-ray. Thus, the design team chose photosensitive materials to print the bony structures of the simulator. The femur and anterior superior iliac spine were fabricated using white polyamide EOS PA2200, while the components of the acetabulum and acetabular labrum were 3D printed as a single piece using the Stratasys J750 3D printer. These components were made from a combination of VeroPureWhite, VeroCyanV, VeroMagentaV, VeroYellowV, and Agilus materials.

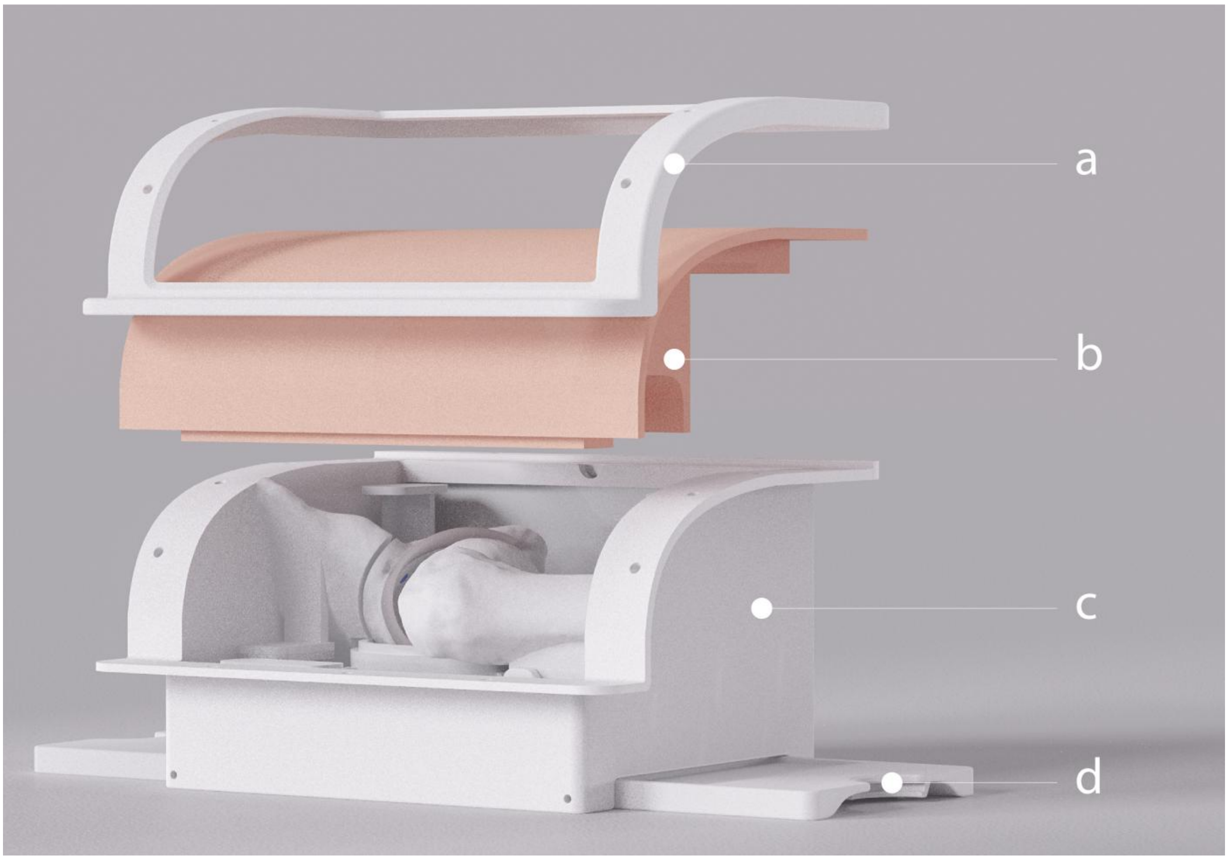

Figure.1 Main components of the simulator: (a). clip frame to fix the soft component, (b). soft component to simulate the soft tissue, (c). container for holding all the bony and supporting structures, (d). bench fixer used in tandem with a bench vise to secure the simulator onto the table (foldable).

To evaluate the simulator's validity, a cross-sectional study involved 29 male orthopedic surgeons from 11 hospitals, aged 23 to 56. Participants were categorized into novice, intermediate, and experienced groups based on their surgical training, with adjustments for individual experience levels. Before the simulation, participants received a 4-hour lecture on hip arthroscopic surgery to familiarize themselves with the procedure. During the simulated operation, an arthroscope and standard surgical tools were used. An instructor with 2 years of hip arthroscopy experience guided the participants, utilizing a task-specific checklist (TSC, Table 1) for evaluation. Trainees were required to follow the TSC protocol to complete 12 surgical steps.Performance was assessed based on task completion time and fluoroscopy usage, with all sessions videotaped. A blinded assessor reviewed the footage using the Arthroscopic Surgical Skill Evaluation Tool (ASSET) and a global rating scale (GRS).

Table 1 Task-Specific Checklist for Hip Arthroscopic Training

	Tasks	Yes	No
1	Mark the surface projection of the anterior superior iliac spine and greater trochanter		
2	Mark the operation area and the operation forbidden area		
3	Mark the anterolateral portal (ALP), mid-anterior portal (MAP), proximal mid-anterior portal (PMAP) and distal anterolateral portal (DALA)		
4	Establish the anterolateral portal (ALP) under fluoroscopy		
5	Insert camera into ALP		
6	Establish the mid-anterior portal (MAP) under the direct vision of arthroscopy (use c-arm fluoroscopy if necessary)		
7	Put the probe into the articular cavity through the MAP		
8	Observe the upper labrum through MAP, point out the labrum at 12 o'clock through ALP with probe		

9	Observe the anterior labrum through ALP, point out the labrum at 2 o'clock through MAP with probe
10	Establish the distal anterolateral portal (DALA) under the direct vision of ALP (use fluoroscopy if necessary)
11	Put the probe into the articular cavity through DALA
12	Observe the anterior inferior labrum. Point out the labrum at 4 o'clock through DALA with probe
13	Establish the proximal mid-anterior portal (PMAP) under the direct vision of ALP (use fluoroscopy if necessary)
14	Put the probe into the articular cavity through the PMAP
15	Observe the upper labrum. Point out the labrum at 1 o'clock through the PMAP
	Number of times fluoroscopy was used

3 RESULTS

3.1 Training surgical skills on hip arthroscopy by simulation

A total of 225 arthroscopic professionals responded to the survey. Ultimately, 159 responses from surgeons at 130 institutions located across 27 provincial administrative districts in China, were finally included in the dataset. Cronbach's Alpha test was performed on the 33 survey questions ($\alpha = 0.967$), showing that the internal consistency of this survey is classified as "excellent". Of the 159 valid responses, 66 were from junior specialist surgeons, 68 responses from consultants, and 25 responses from senior consultants. The average number of years of experience for performing arthroscopy was 8.48 (±4.71), while the average number of arthroscopic operations per year was 267.5 (±241.1). Details of the participants' demographic information are presented in Table 2.

Table 2 Participants demographics for the online survey

	Number of participants n	Average years of performing arthroscopies mean (± SD)	Average number of arthroscopic operations per year mean (± SD)	Total number of hip arthroscopic operations mean (± SD)
Junior Specialist Surgeonsa	66	5.39 (± 2.80)	164.12 (± 134.96)	178.71 (± 252.79)
Consultantsb	68	9.71 (± 3.86)	276.93 (± 179.22)	377.71 (± 435.65)
Senior Consultantsc	25	13.28 (± 5.25)	514.80 (± 257.71)	1050.48 (± 980.02)
All participants	159	8.48 (± 4.71)	267.50 (± 214.08)	400.89 (± 583.73)
Total number of Provincial administrative district in China	34	Surveyed provincial administrative districts	27	Coverage 79.4%

*a compared with b, **; a compared with c, ****; b compared with c, ****

**represents P < 0.01; ****represent P < 0.0001*

Table 3 Categories of specific surgical skills important for trainees to possess prior to performing in operating room, rated by surgeons with different levels of experience

Value	Junior specialist surgeons Mean (± SD)	Consultants Mean (± SD)	Senior consultants Mean (± SD)	All participants Mean (± SD)
Identification of structures and navigation of the arthroscopea	4.15 (± 0.81)	4.20 (± 0.68)	4.09 (± 0.78)	4.16 (± 0.76)
Instrument handlingb	4.11 (± 0.81)	4.07 (± 0.65)	4.06 (± 0.76)	4.09 (± 0.74)
Preparation of the patient and instrumentsc	3.84 (± 0.86)	3.92 (± 0.77)	3.63 (± 0.96)	3.84 (± 0.85)

*a compared with c, ***; b compared with c, **

**Represents P < 0.05; ***Represents P < 0.001*

As shown in Table 3, surgeons considered skills related to the identification of structures and navigation to be the most important preparation for trainees before they perform the actual surgery. A post-hoc Tukey test revealed that skills related to the preparation of patients and instruments were significantly lower than those in the other two categories (P < 0.05). No significant differences were found when comparing the scores from surgeons with different levels of experience for each individual category.

Based on the mean scores, there are ten skills ranging from treatment of cam deformity (where the head of the femur does not sit symmetrically on the neck) to establishing the anterolateral portal under fluoroscopic guidance were rated over 4.2. This indicates that these skills are extremely important for hip arthroscopic surgery, trainees should pay extra attention to these areas during their training.

Table 4 Usefulness of simulation type in preparing trainees to perform in the operating room, rated by surgeons with different levels of experience

Value	Junior specialist surgeons Mean (± SD)	Consultants Mean (± SD)	Senior consultants Mean (± SD)	All participants Mean (± SD)
Simulation using cadaveric specimensa	4.48 (± 0.89)	4.57 (± 0.77)	4.40 (± 0.75)	4.51 (± 0.82)
Simulation using high-fidelity physical simulatorsb	3.95 (± 0.99)	3.59 (± 1.02)	3.08 (± 0.80)	3.77 (± 0.99)
Simulation using virtual reality simulatorsc	3.77 (± 1.06)	3.38 (± 1.11)	3.64 (± 0.93)	3.58 (± 1.08)
Simulation using low-fidelity bench top modelsd	3.08 (± 1.09)	2.88 (± 1.13)	3.16 (± 1.25)	3.01 (± 1.14)

*a compared with c, ****; a compared with c, ****; a compared with d, ****; b compared with d, ****; c compared with d, *****

*****Represents P < 0.0001*

Surgeons were asked to rank the usefulness of the four most common types of simulation for practicing surgical skills: 1) cadaveric specimens, 2) virtual reality (VR) simulators, 3) high-fidelity physical simulators, and 4) low-fidelity bench-top models. As shown in Table 4, cadaveric specimens were rated as the most useful, significantly outperforming the other three methods.

The differences in rankings among the four simulation methods were statistically significant (P < 0.01). Tukey's test for pairwise comparisons revealed significant differences between all pairs (P < 0.01), except between the VR simulator and high-fidelity physical simulators (P = 0.35). Surgeons, regardless of their experience level, consistently prioritized higher fidelity simulation over lower fidelity options.

In the open comment section, participants suggested that additional factors, such as medical image interpretation, joint traction time, and familiarity with equipment should be included in the survey, as these are also crucial for the successful performance of arthroscopic surgery.

3.2 Development and validation of the Three-Dimensional (3D) Printed Simulator

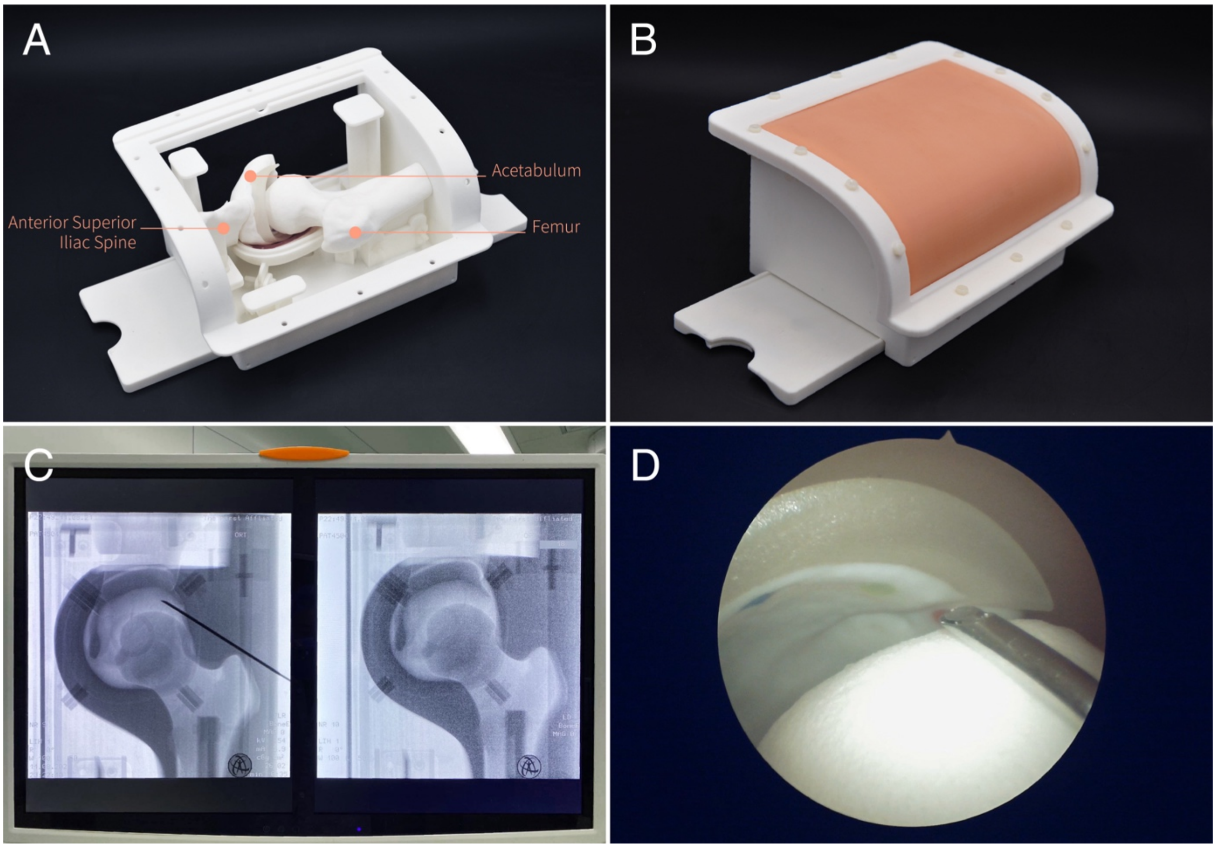

Figure.2 The 3D printed simulator: (A) The 3D printed bony structures of the simulator; (B) Assembled simulator with the silicon component; (C) Fluoroscopic images for the portal placement process; (D) Arthroscopic view of the process for establishing the distal anterolateral (DALA) portal.

The simulator was designed to be secured onto the table by using two bench vises (Figure 2A). The materials of the simulator are photosensitive to radiography and all the internal structures are visible by fluoroscopy (Figure 2C). The anatomical landmarks of the anterior superior iliac spine and the greater trochanter can be identified by palpating the simulated soft tissue(Figure 2B). When viewed using the arthroscopic camera, the intra-articular anatomical structures of the simulator appear similar to that observed in the hip joint of the human body (Figure 2D).

To evaluate the developed simulator, all participants performed the required operational steps on the 3D printed simulator. Cronbach's alpha values of 1 for the total ASSET score and 0.7 for the task-specific checklist, indicate good internal consistency and reliability. Cohen's f values for task-specific checklist, ASSET and final GRS were 0.9, 2.7 and 1.9 respectively, where f values above 0.4 are considered to have a large effect size for one-way ANOVA analysis.

One-way ANOVA analysis revealed significant differences between the 3 subgroups with varying levels of experience for the total checklist score ($F_{2,26} = 11.3$) (Figure 3A), total ASSET score ($F_{2,26} = 92.1$) (Figure 3B), overall final GRS score ($F_{2,26} = 49$) (Figure 3C), the number of times the participants used fluoroscopy ($F_{2,26} = 7.4$) (Figure 4A) and completion time for tasks ($F_{2,26} = 23.5$) (Figure 4B). Positive correlations were observed between clinical experience and total ASSET score (hip arthroscopy $r = 0.6$; shoulder arthroscopy $r = 0.5$; knee arthroscopy $r= 0.5$). Negative correlations were seen between clinical experience and the completion time for tasks (hip arthroscopy $r= -0.6$; shoulder arthroscopy $r = -0.5$; knee arthroscopy $r= -0.5$).

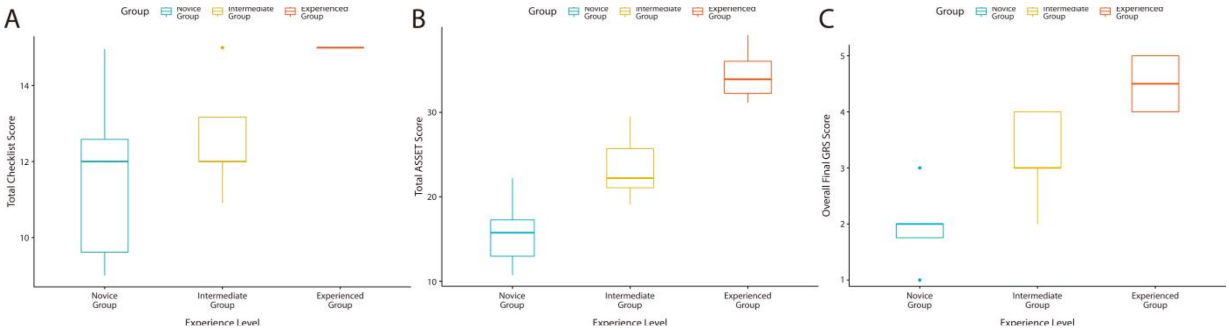

Fig.3 Box plots of the different assessment tools for the three groups with varying experience levels (Novice vs. Intermediate vs. Experienced). A Total checklist score; B Total Arthroscopic Surgical Skill Evaluation Tool (ASSET) score; C Final Global Rating Scale (GRS)score by experience level

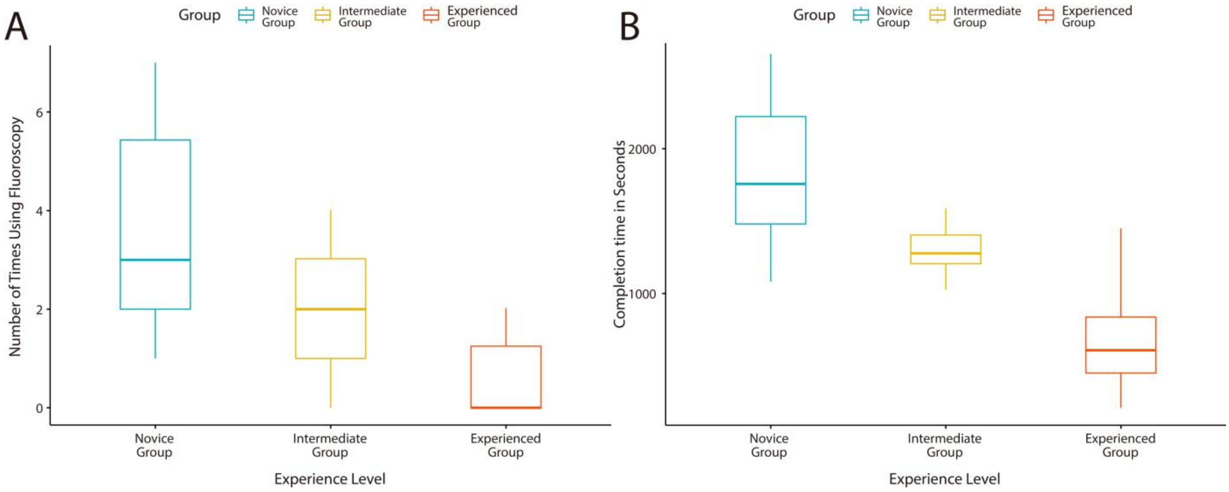

Fig.4 Box plots of task completion for the three groups with different experience levels (Novice vs. Intermediate vs. Experienced). A Number of times fuoroscopy was used; B Task completion time

4 DISCUSSION

The results of the survey aligns with earlier research on Canadian orthopedic professionals although the focus was on arthroscopy of a different joint, highlighting the convergence of training methods between Canada and China [19], [20], despite focusing on different joints. Hip arthroscopy has proven to be a valuable technique, though early challenges stemmed from the complex anatomy of the hip. Surgeons consistently rated cognitive skills, especially anatomical knowledge, as more critical than motor skills, particularly in complex procedures like portal placement.

A large number of specific skills have been highlighted as essential for optimal clinical outcomes, reflecting the steep learning curve associated with this procedure.Several key skills have been identified as the top skills required for hip arthroscopy, with a focus on FAI surgery. There are reports highlighting that high-impact athletic activities during growth, such as playing soccer, basketball, and ice hockey during adolescence can cause FAI [21], [22]. Therefore, a large population, ranging from younger to elderly individuals, could be affected. Hip arthroscopy, the most common surgical technique to address various types of FAI, has shown optimal clinical outcomes [23], [24].

Cadaveric simulation remains the preferred training method, offering unmatched anatomical accuracy and tactile feedback, but faces challenges related to availability and cost [25], [26]. As alternatives, high-fidelity physical simulators and VR simulators were identified as useful tools for training [27]. High-fidelity physical simulators offer detailed anatomical accuracy and haptic feedback [28], while VR simulators provide varied functions and immediate feedback, though concerns remain about their cost-effectiveness [29]. Low-fidelity models, while less favored, still provide value in helping trainees familiarize themselves with surgical instruments and basic skills [30], [31]. According to the results of the survey study, the high-fidelity 3D printed simulator has been designed and manufactured. Combining medical imaging, CAD, and 3D printing, the simulator

replicates critical techniques like portal placement and arthroscope navigation.
In the validation study, participants' performance correlated with their experience level, validating its effectiveness. Experienced participants completed tasks faster, used fluoroscopy less, and scored higher, proving the simulator's usefulness as an objective assessment tool. Analysis of the data collated in validation study shows a link between the participants' prior arthroscopic experience and their performance during the simulated operation. Compared to participants with lesser experience, more experienced participants tend to complete the simulated task in a shorter period of time, using fluoroscopy less frequently, and obtaining higher scores in task-specific checklist, ASSET, and final GRS. These results show that the simulator can be used as an objective assessment tool to help orthopedic surgeons gauge the competence level of the trainees' surgical skills for performing hip arthroscopy. According to the post-study feedback, the 3D printed simulator received favorable feedbacks from the participants. Most of the participants were satisfied with the fidelity of the simulator, and were of the opinion that the intra-articular anatomical structures and realistic tactile feeling of the soft tissue closely resemble that of the human body.
For simulation-based training, cost is always an important aspect as it relates to the sustainability of its usage. Compared to other virtual reality (VR) based or benchtop simulators, the cost of this 3D printed simulator is relatively low. The overall material cost for the simulator is around USD $295. For the simulation practice, the soft component that mimics the soft tissue can be disposed after multiple operations and the replacement cost of the soft component is only around USD $78. Clearly, the 3D printed simulator is a cost-effective tool and is a highly affordable option for most of healthcare institutions. Meanwhile, since the validation study has proved that the developed simulator has properly replicate the clinical conditions of hip arthroscopy, it would seem that such a 3D printed simulator can be used routinely to assist the learning and practicing relevant hip arthroscopic skills. It may help arthroscopic professionals improve their learning efficiency and be used for preliminary training, refresher courses and simulation of complex scenarios before actual surgeries, which in turn can possibly help reduce the risk of medical errors in the operating room, and hence enhance patient's safety.

5 CONCLUSION

This study has revealed the specific requirements for hip arthroscopic training. Accordingly, the reliable 3D printed high-fidelity simulator has been developed, which can be used for training and assessing hip arthroscopic skills. This study has illustrated an effective approach for medical innovation, based on the collaboration between product designers and medical experts, it is possible to develop the effective tools and training program for surgical education, which can benefit novice surgeons and the quality of healthcare.

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