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ORIGINAL ARTICLE

Assessment of the proficiency level of novices in distal intramedullary nail interlocking achieved through training with Digitally Enhanced Hands-on Surgical Training (DEHST)

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Abstract

Background Digitally Enhanced Hands-on Surgical Training (DEHST) platform was introduced to overcome the lack of training capabilities for the challenging task of freehand distal interlocking of intramedullary nails. It demonstrates high perceived realism for surgeons, and novices perform significantly better after DEHST training. However, characterization of how performance improves remained unexplored. The aim of this study was to evaluate the training progression of novices in freehand distal interlocking during five training rounds with DEHST and to compare their performance in a simulated operation against experienced surgeons.

Methods Ten novices (Group 1) underwent five DEHST training sessions (approximately one hour in total) and their performance data was acquired and evaluated. The surgical performance of Group 1 was compared with ten surgical experts (Group 2) by performing distal interlocking of a real tibia nail in an artificial bone model in a simulated operation. Time taken, number of X-rays, accuracy of nail hole roundness, and success rates were compared between the groups.

Results Group 1 achieved comparable performance to Group 2 in number of X-rays 26.0 (range 15–40) versus 22.5 (range 16–34), $p = 0.281$, and accuracy of hole roundness 95.0% (range 91.1–98.0%) versus 93.3% (range 90.7–95.9%), $p = 0.087$. However, Group 1 needed significantly longer time compared with Group 2, $p = 0.001$, and furthermore, one participant in Group 1 (10%) failed to hit the nail hole with the drill bit, while 100% of the participants in Group 2 were successful.

Conclusions DEHST appears to be a useful tool to gradually improve the proficiency level of novices and to train relevant practical surgical skills needed for distal interlocking of intramedullary nails. However, further investigations are needed to demonstrate the performance under the conditions of a real operation.

Keywords Education · Simulation · Distal interlocking · Intramedullary nailing · Training

Background

Freehand distal interlocking of intramedullary nails is a challenging task that surgeons need to master during their training. The technique requires a precise insertion of a screw into a pilot hole in the bone and a hole in the nail with the use of an intraoperative image intensifier. In contrast to short nails that can be locked with the help of an extracorporeal aiming arm, long nails normally are locked distally using a freehand technique [1, 2]. This is due to alignment errors of targeting jigs related to the length of the needed jig. Despite the numerous devices proposed to assist the surgeon during this demanding procedure [1–12], none of them could completely solve this problem. Therefore, surgeons continue to apply predominantly the freehand technique [3]. Once mastered, not only can freehand insertion be faster, but the same technique is needed for the insertion of poller screws—a critical skill needed for the management of the same injury patterns. Moreover, in case of an intraoperative technical device failure, the surgeon needs to be able to finish the surgery without an aiming arm [13, 14]. So far, the training options for this maneuver were very limited. The AO Research Institute Davos has now developed a Digitally Enhanced Hands-on Surgical Training (DEHST) platform to address this issue [8]. The corresponding device allows the user to practice the surgical steps of freehand intramedullary

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nail interlocking without the use of radiation. In the first step of the validation cascade, DEHST could already reliably discriminate between novices and surgical experts, and face and construct validity were established [15]. Moreover, surgical novices performed significantly better in a simulated operation after five training rounds with DEHST than novices without DEHST training [16]. For translation of these results into clinical practice, evaluation was required of the proficiency of novices gained throughout their training. Therefore, during this study, the performance metrics of novices acquired during five exercises with DEHST were evaluated and their surgical performance was compared with that of experienced surgeons during a simulated operation.

Materials and methods

Participants and study groups

Twenty participants were recruited from April to July 2022 at our level 1 trauma center and assigned to two study groups as follows. Group 1 contained novices (n = 10) being either interns or first-year residents without surgical experience in distal intramedullary nail interlocking, who underwent a standardized training with DEHST. Group 2 contained experts (n = 10) being consultants or senior consultants with a minimum of 30 performed operations in distal nail interlocking. An obligatory questionnaire containing personal data and information about prior experience in distal interlocking was completed by all participants. Exclusion criteria for Group 1 were prior surgical experience in distal nail interlocking and an inability to perform the standardized training.

Digitally Enhanced Hands-on Surgical Training (DEHST)

DEHST is a platform for modular surgical skills training developed at the AO Research Institute Davos. The first realized training module is designed for practicing the freehand technique for distal intramedullary nail interlocking (Fig. 1). It consists of a scaled image intensifier (C-arm) model that can be aligned in all six degrees of freedom and is complemented by a power drilling machine with an angular drive. By pressing a footswitch, the position of the drilling machine and the C-arm are tracked via an optical camera system [10] and a simulated X-ray image is displayed on the computer screen. Users can practice the required surgical steps of the freehand technique for distal interlocking as described by Medoff et al. [2] and later modified by Kelley et al. [1] as follows (Fig. 2). Step 1: alignment of the C-arm in all six degrees of freedom to achieve a perfect circle projection of the targeted nail hole centred on the screen. Step 2: placement of the drill bit tip in the middle of the perfect circle, right over the nail hole. Step 3: alignment of drill bit parallel to the virtual X-ray beam to achieve a 'bulls-eye-shot'. Step

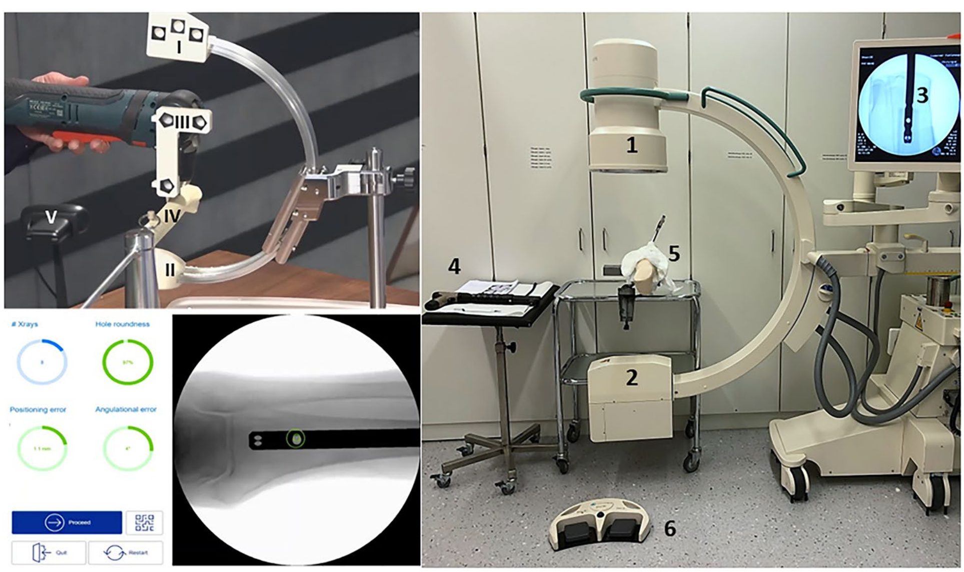

Fig. 1 Top left: overview of DEHST. I: Receiver of C-arm model with reference markers; II: X-ray tube of C-arm model; III: drilling machine with angular drive and reference markers; IV: distal tibia model; V: conventional optical camera. Bottom left: view of the computer screen with simulated X-ray images and performance metrics. Right: equipment and setup for simulated operation. 1: Receiever of real C-arm; 2: X-ray tube of real C-arm. 3: X-ray image of real tibia nail; 4: drilling machine with angular drive, printed manufacturers guidelines, and scalpel; 5: distal tibia model with a foam coverage and an intramedullary placed tibia nail; the rest of the leg covered with a blanket to simulate soft tissue coverage of the whole tibia; 6: footswitch

Fig. 2 Four essential steps for a successful freehand distal intramedullary nail interlocking. Top left: first picture to gain overview and orientation. Top right: C-arm aligned to achieve a 'perfect circle' hole projection centered on the screen. Bottom left: Drill bit tip positioned in the center of the 'perfect circle' after cutting of the foam cover with knife. Bottom right: Angular drive with the drill bit brought parallel to the X-ray beam to achieve a 'bulls-eye-shot'. Subsequently, the hole through the nail is drilled in this position

4: real drilling through the nail hole and both cortices of the provided artificial tibia bone model. Performance metrics in terms of number of X-rays, hole roundness, angulation and positioning error during drilling are generated during training and displaced on the computer screen.

All novices (Group 1) completed a standardized training for one hour with DEHST after a short familiarization with the components of the system. Except for this short technical instruction to the system and its components, no additional training was performed and no tips were given to them. By using only the official manufacturer's instructions (pages 19–20) [17] and the corresponding distal interlocking module described on the AO Surgery Reference website [18], the necessary surgical steps for successful distal interlocking were presented to the novices. By doing this, a scenario was simulated where DEHST is used as a tool for training of young surgeons without the assistance of senior surgeons. The DEHST training comprised five rounds of freehand distal nail interlocking of one virtual screw hole each. Participants results and performance metrics were presented on the computer screen, demonstrating the individual performance of each participant (e.g., angular deviation, roundness of the 'perfect circle'). Novices had to translate this feedback into performance improvements themselves during the next training round. No feedback was provided by the supervising authors of the current study. Furthermore, novices were not provided with any guidelines regarding time, number of X-rays or training procedure, and they were free to train at their own discretion.

Assessment of proficiency through a simulated surgery

All expert surgeons (Group 2, without DEHST training) and all novices (Group 1, one week after DEHST training) performed a simulated operation using the freehand technique to interlock a real tibia nail (300 mm Expert Tibia Nail, Ø 10 mm, Johnson&Johnson MedTech, Zuchwil, Switzerland) in an artificial tibia model (tibia right distal, 3108, SYNBONE AG, Zizers, Switzerland) covered with a foam model (PR2000.10, SYNBONE AG, Zizers, Switzerland) and using a surgical C-arm (Siemens ARCADIS Varic, Siemens Medical Solutions AG, Erlangen, Germany) (Fig. 1). As in the DEHST training rounds, the goal of this operation was to hit the distal anteroposterior hole of the nail with the drill bit and complete the task via penetration of the posterior cortex. The task completion was considered successful if the drill bit was in the nail hole. If it was not, the procedure was rated as failed. The following test setup was used. The artificial tibia was mounted in supine position with the distal anteroposterior hole of the nail facing variably upwards within a cone of 15°. A new random nail position was selected for each participant. All participants were assisted during the operation by the senior author. However, only movements of the C-arm were locked or unlocked on command and no help was provided with the actual C-arm movement. This step was necessary, as the C-arm would spontaneously move due to the gravity if the movements were not blocked. A lowest-height anteroposterior starting C-arm position, 20 cm distal and 20 mm lateral to the medial malleolus, was set for each participant. The necessary surgical steps to hit the nail successfully with the drill bit are visualized in Fig. 2. Additionally, the participants had to cut the foam coverage—simulating soft tissue and skin coverage of the tibia—with a knife to position the tip of the drill bit on the tibia. The expert surgeons (Group 2) performed the same operation without prior DEHST training, with assistance of the senior author in C-arm handling as done for Group 1. All participants read the official manufacturer's instructions (page 19–20) [17] and the corresponding distal interlocking module described on the AO Surgery Reference website [18] prior to the simulated operation.

Data acquisition

Performance data of Group 1 were collected during their DEHST training. The following metrics were obtained and statistically evaluated: (1) number of theoretical X-rays and

(2) time to complete the task, (3) roundness of the nail hole to assess the 'perfect circle' projection and thus the correct alignment of the C-arm, (4) drill bit position accuracy in relation to the center of the nail hole, and (5) angular deviation of the drilling trajectory from the hole axis after drilling. (6) Hit and thus successful interlocking of the virtual nail during training was defined as an angular deviation of less than 10° and a positioning offset within the range of 2 mm from the hole center. These values were defined from the geometry of the nail hole.

During interlocking of the real tibia nail during the simulated operation, the following metrics were obtained in both groups: (1) time (to achieve a perfect circle, to position the drill bit tip and to complete the task), (2) number of X-rays (to achieve a perfect circle, to position the drill bit tip and to complete the task), (3) radiation exposure (overall radiation exposure and time of X-ray exposure), (4) hole roundess to assesses 'perfect circle' alignment and its corresponding angulation of the nail hole axis with regard to the X-ray beam, and (5) successful completion of the task (hit or miss the nail hole). Radiation exposure and time were obtained from the radiation report of the C-arm. Roundness of the perfect circle alignment was evaluated from the last X-ray prior to drill tip positioning as previously described (100% for perfectly circular hole projection, 0% for no projection visible) [15]. Furthermore, critical events defined by major slippage of the drill into the soft tissues of more than 1 cm were documented.

Statistical analysis

Statistical analysis was performed using SPSS software package (v.27, IBM SPSS, Armonk, NY, USA). Shapiro-Wilk test was used to screen and prove normality of the numerical data distribution. Independent-Samples *t*-test and Chi-Square test were applied to detect significant differences between the groups with regard to the numerical and categorical data, respectively. General Linear Model Repeated Measures was used to detect significant differences in progression of the performance metrics over the DEHST training course of five rounds. Level of significance was set to 0.05 for all statistical tests.

Results

Participants

No prospective participants had to be excluded. Group 1 consisted of six female and four male novices ($n = 10$), average age 26.0 years (range 24–30 years, SD 1.7). Eight were interns and two residents in their first year. Eight of the novices were right-handed. Group 2 consisted of two female and eight male experts ($n = 10$), average age 38.9 years (range 34–48 years, SD 4.6). Nine worked as consultants and one as a senior consultant. Nine of the experts were right-handed. On average, Group 2 participants had previously performed an average of 177 (range 30–500, SD 280) freehand distal interlocking procedures of an intramedullary nail.

Training progress

The results after each DEHST training round of the novices (Group 1) are presented in Table 1 and Fig. 3. All investigated performance metrics improved over the course of five rounds. Hole roundness improved significantly ($p = 0.007$), and trends towards significance were observed with regard to reduced number of X-rays, increased angular accuracy, decreased time for task completion, and increased number of successfully completed tasks ($0.057 \leq p \leq 0.084$). All other metrics were not significantly changed over the course of 5 rounds.

Surgical performance

The results from the simulated operation are presented for each separate group (trained novices in Group 1 and experts in Group 2) in Table 2. No critical events such as major slippage of the drill into the soft tissues were observed in either group during the operation. In Group 1, 90% of the participants achieved successful completion of the task (hitting the

Table 1 Performance metrics after each training round with DEHST in Group 1 (novices) presented in terms of mean value and range, together with p-values for their progression over the course of five rounds

Performance metrics	Round 1	Round 2	Round 3	Round 4	Round 5	p-value
Number of X-rays (n)	30 (11–69)	40 (11–86)	25 (7–42)	29 (20–49)	23 (11–35)	0.064
Roundness perfect circle (%)	85 (75–94)	90 (75–96)	93 (83–99)	91 (81–97)	93 (83–99)	0.007
Drill bit tip position (mm)	6 (1–24)	3 (1–9)	2 (1–4)	3 (1–20)	2 (1–4)	0.351
Angle (°)	9 (2–19)	8 (2–14)	5 (1–9)	7 (3–10)	5 (1–9)	0.057
Time (s)	345 (76–675)	422 (196–1020)	262 (106–384)	339 (216–642)	245 (130–343)	0.084
Task successfully completed (n)	3 / 10	3 / 10	5 / 10	7 / 10	7 / 10	0.074

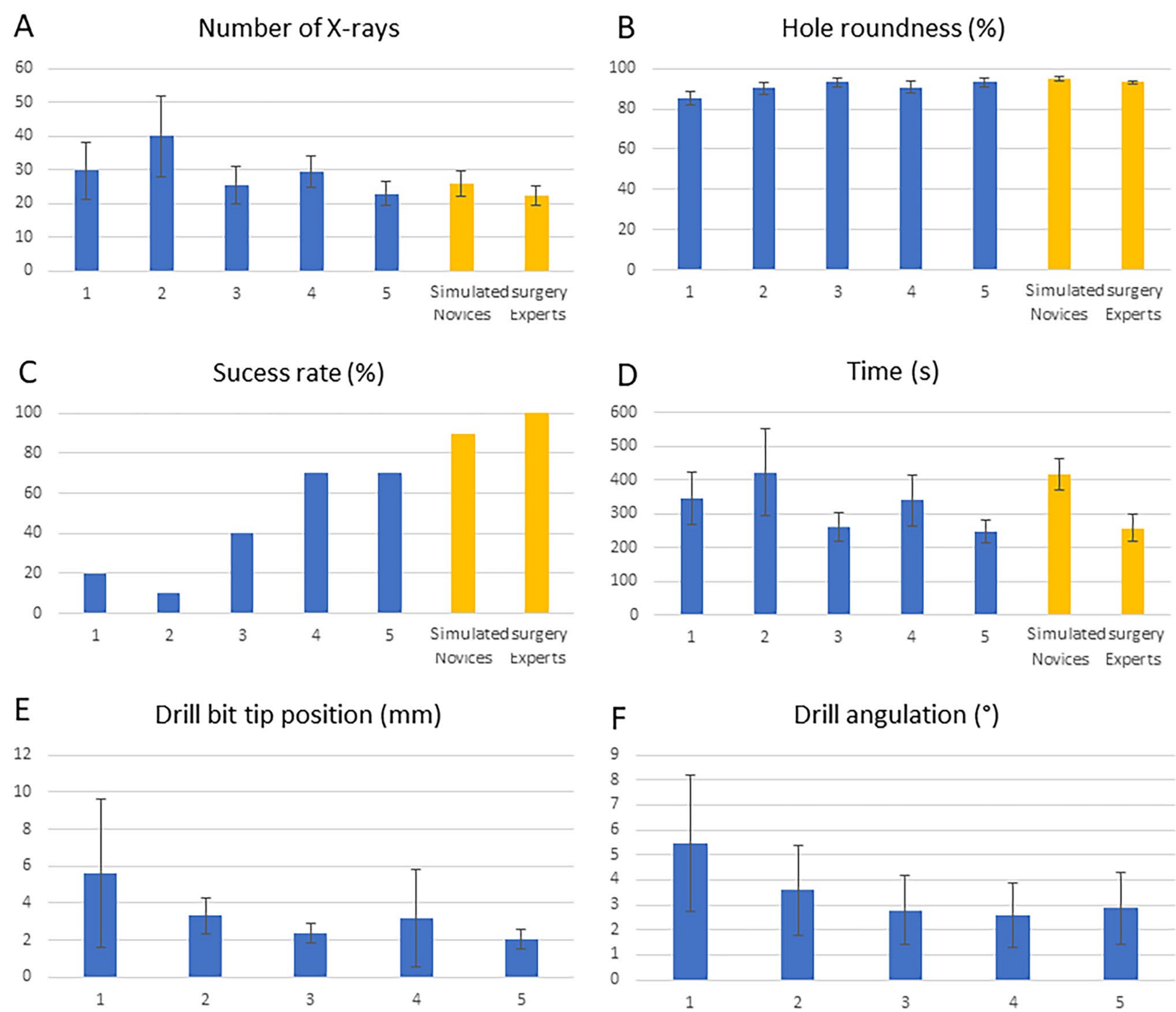

Fig. 3 Blue: performance metrics of Group 1 (novices) over the course of five training rounds (1–5) with DEHST; yellow: performance metrics of both groups during the simulated operation; stars (*) indicate significant differences; **A** number of X-rays; **B** hole roundness; **C** success rate (percentage of successfully completed tasks); **D** time to complete the task; **E** drill bit tip position in relation to the centre of the virtual hole; **F** drill bit axis angulation in relation to the virtual hole axis

nail with the drill bit), whereas 100% of the experts in Group 2 achieved this ($p=0.305$). Hole roundness of the perfect circle was 95.0 ± 2.3% (mean value ± standard deviation) in Group 1 and 93.3 ± 1.8% in Group 2 ($p=0.087$). This corresponded to an angulation of the nail hole axis of 2.0° ± 1.0° in Group 1 and 2.7° ± 0.8°, in Group 2 with regard to the C-arm X-ray beam ($p=0.116$) (Fig. 4). None of the participants ended up with oval drill holes of the cortices as a result of an inaccurate drill bit tip position and angulation.

In addition, the performance metrics of the final round 5 of the DEHST training in Group 1 and those from the simulated surgery in the same group demonstrated no significant differences for number of X-rays to complete the task, roundness of the perfect circle, and number of successfully completed tasks ($p \geq 0.264$), except for time to complete the task, that was shorter during the training ($p=0.001$).

Discussion

The aim of this study was to analyze the training performance of surgical novices in freehand distal intramedullary nail interlocking during five self-explanatory rounds of training with DEHST and compare their change in performance against expert surgeons in a simulated operation.

Table 2 Performance metrics from the simulated operation in each separate group, presented in terms of mean value and range, together with p-values from the comparisons between the 2 groups

Performance metrics	Group 1 (trained novices)	Group 2 (experts)	p-value
Time to perfect circle (s)	160.3 (80–320)	95.5 (59–121)	0.019
Time to drill tip position (s)	310.3 (215–529)	204.7 (118–430)	0.020
Time to complete task (s)	414.7 (290–615)	256.1 (180–448)	0.001
Number of X-rays to perfect circle (n)	7.1 (3–13)	6.0 (3–9)	0.352
Number of X-rays to drill bit tip position (n)	16.7 (15–40)	15.4 (8–29)	0.631
Number of X-rays to complete task (n)	26.0 (15–40)	22.5 (16–34)	0.281
X-ray exposure (μGcm^2)	17.8 (9.8–26.4)	15.5 (11.5–29.1)	0.354
Time of X-ray exposure (s)	22.5 (13–34)	19.3 (14–35)	0.294
Roundness perfect circle (%)	95.0 (91.1–98.0)	93.3 (90.7–95.9)	0.087
Angulation (°)#	2.0 (1–4)	2.7 (2–4)	0.116

Data for Group 1 already reported in [16]

#Angulation of the C-arm X-ray beam with regard to the nail hole axis

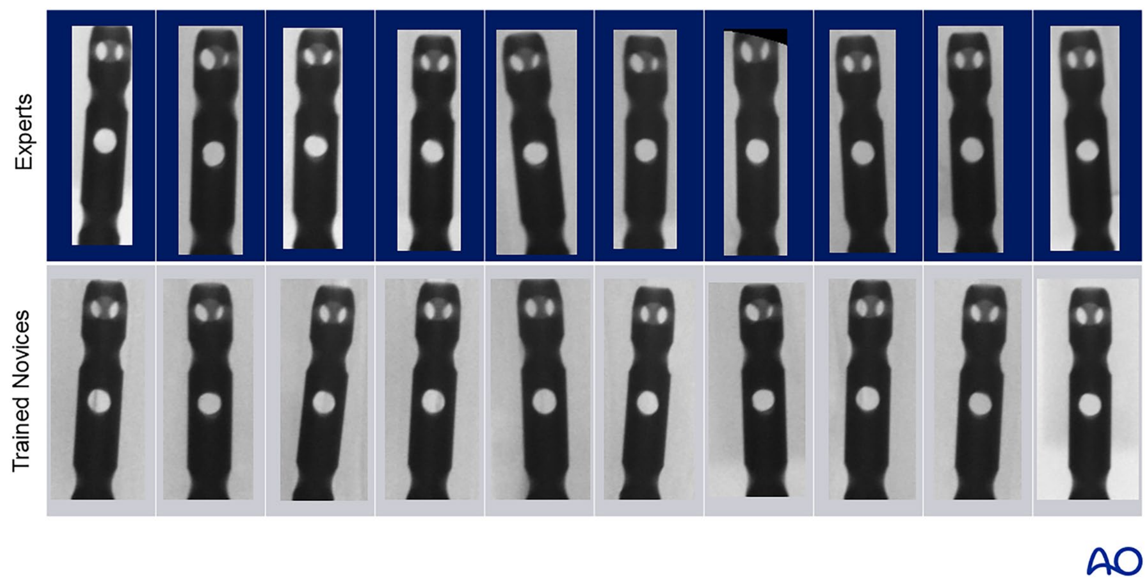

Fig. 4 'Perfect circle' images of all participants during the simulated surgery prior to drill bit tip positioning. Bottom: Group 1 (trained novices, already reported in [16]). Top: Group 2 (experts). Both groups demonstrated a comparable 'perfect circle' alignment of the anteroposterior nail hole

During the DEHST training, the performance of the novices improved over the course of the five training rounds. The hole roundness improved significantly, and a trend towards significance was observed with regard to reduced number of X-rays, increased angular accuracy, decreased time for task completion, and increased number of successfully completed tasks. Large data scattering during the different training rounds, resulting from different behavioral patterns of the novices, may have prevented registration of further significant changes. Some novices took their time to analyze the results or played with different C-arm angles to observe the influence on the perfect circle alignment. The main focus of the DEHST training was not to finish the task as fast as possible, but to achieve the best possible learning effect. Furthermore, some novices finished their first round extremely fast, with a very low number of X-rays, ending up with a failure due to poor surgical technique and knowledge. The participants seemed to reflect on feedback after round 1 for self-assessment of their performance in order to apply this in the following rounds, resulting in a high accuracy of the hole roundness. To achieve this, they took more time in round 2 and clearly needed more X-rays. After round 4, an acceptable result was achieved with a success rate of 70% and high scores in roundness, time, and X-rays needed.

The current study was designed to observe young unexperienced surgeons during a self-explanatory training with DEHST. Therefore, all novices were provided with the official manufacturer's guidelines [17] and the corresponding distal interlocking module described on the AO Surgery Reference website [18] prior to training, to mimic a scenario where young surgeons prepare themselves for a simulator training, thus reducing support and personnel costs during an on-site application in hospitals. Nowadays, medical doctors spend more time for administrative tasks [19, 20] and face a steadily growing workload [21, 22], reducing their time for teaching and learning. Considering the increasing financial burdens of the healthcare systems, DEHST was developed to be easy to operate and affordable in all hospitals. Another possible application for DEHST would be during such AO educational offerings as basic and advanced courses with teaching instructors, where the surgical task for distal intramedullary nail interlocking is not implemented so far. It is expected that this would further increase the training effect of the system; however, further investigations are necessary to proof this hypothesis.

The most important finding of the current study is that the novices trained with DEHST achieved a good level of proficiency as their performance in terms of number of X-rays, accuracy of hole roundness, and successfull drilling was comparable with those of the experts during the simulated surgery. This should translate into a more precise surgery and a reduced radiation exposure for both the involved medical personnel and patient as freehand distal interlocking of intramedullary nails requires up to 33% of the overall radiation exposure [23]. However, during the simulated surgery the novices needed significantly longer time to complete the task, which could be an indication of uncertainty. This result is not surprising as in contrast to the experienced surgeons, most of them used a real C-arm and/or a power-drilling machine with an angular drive for the first time on their own during both the DEHST rounds and simulated operation. At the AO Davos Courses in 2021 DEHST already discriminated between experts and untrained novices by indicating significantly better performance metrics for the experts [15]. Although this difference was identified during simulator training only, it is obvious that it would be existing in everyday clinical practice. The findings of the current study are in line with other reports on simulator-based training resulting in a positive effect on real surgical tasks [24–26].

The good performance of the novices during the simulated surgery also demonstrated that the relevant practical skills for distal interlocking were developed through DEHST and the participants were able to apply these skills in a surgical-like setting. Except for the needed time, the scores from the final round of the DEHST training match to those from the simulated surgery—with no significant differences—demonstrating that the DEHST training appears to be realistic.

One novice failed to hit the nail successfully with the drill during the simulated operation, whereas all experts completed the task successfully. In an operation with a real patient, the surgical step of distal interlocking would have to be performed under more complex circumstances leading to an increased radiation exposure, a longer operation time and in the worst case may have a catastrophic influence on bone healing due to possible weakening of the screw purchase in the bone [27]. This finding underlines the importance of other training modalities, e.g., training with an experienced surgeon is also needed as the autodidactic DEHST training might not fully compensate for an expert-guided training in real patients.

Methodological considerations

This study has some limitations. First, all participants needed obligatory assistance during the handling of the C-arm by the senior author due to the influence of gravity to its orientation, that theoretically could have influenced their behavior. However, the movements of the C-arm were only locked or unlocked on command and no assistance for orientation of the C-arm was provided. Second, the number of training sessions of the novices was limited to five self-explanatory rounds without explanatory support of a senior surgeon. Further training rounds with assistance of an expert might have enhanced the novices' performance. Therefore, the evaluated performance metrics during the five training rounds with DEHST may have not considered the real training potential of the novices. Third, the training with DEHST was performed without time pressure or need to minimize radiation exposure. Further investigation is necessary to evaluate the training progress in another cohort of untrained novices under more time pressured conditions. Fourth, a power drilling machine with a 90° angular drive was used in the current study, which enables the surgeon to perform a 'bulls-eye-shot' prior to drilling. Yet, some surgeons applied another technique by bringing a normal power-drilling tool in line with the X-ray beam. Although DEHST is capable to train this technique too, it was decided to integrate the angular drive for DEHST as surgeons' feedback during the AO Davos Courses in 2021 were in its favor. Fifth, the number of participants in the current study was rather low. Nevertheless, a priori power analysis resulted in a minimum of 8 participants per group for statistical power of 0.8 at a level of significance 0.05 under the assumption that the standard deviation in each group is not bigger than 80% of the minimum difference in mean values between the groups. The data for the power analysis was obtained during a pilot test with two DEHST trained participants and two experts. Furthermore, the total number of 20 participants is similar to several previous studies evaluating medical training devices [12, 16, 28–38]. Sixth, the current study did not fully address potential biases or confounding factors that could have influenced the outcomes, such as prior surgical experience of the novices or the expertise of the trainers, however, care was taken by the authors to not interfere with novices during their DEHST training or simulated surgery. Finally, the current study evaluated only novices without surgical experience versus expert surgeons. Therefore, further studies are needed to investigate whether more experienced surgeons or even experts would also benefit from DEHST. Furthermore, it is unclear whether novices trained with DEHST can preserve the obtained surgical skills over a longer time. Future research could examine the DEHST novices again to answer this question.

Conclusion

DEHST appears to be a useful tool to gradually improve the proficiency level of novices and to train relevant practical surgical skills needed for distal interlocking of intramedullary nails. However, further investigations are needed to demonstrate the performance under the conditions of a real operation.

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Author contributions TaP, JB, BeG, BoG and ToP: designed the study. ToP, JB, TaP and ML performed DEHST training and simulated operation. TaP, JB and ToP obtained data. BoG and JF performed statistical analysis. TaP, JB, BoG, FB and ToP interpreted results. GR and BL supervised the study. JB developed the DEHST system. TaP, JB and ToP wrote the original draft of the manuscript, which was next revised in detail first by FB, BL, BeG, JF, BoG and ToP. Subsequent drafts were prepared by all authors. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethics approval and consent to participate All procedures performed in this study were followed in accordance with relevant guidelines. A written informed consent was signed by all participants that their anonymized data would be used for research purposes. Since no patient charts were used, institutional review board approval was not necessary.

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