

Evaluation of a virtual-reality-based simulator using passive haptic feedback for knee arthroscopy

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Received: 11 July 2013 / Accepted: 30 January 2014 / Published online: 12 February 2014
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Abstract

Purpose The aim of this work is to determine face validity and construct validity of a new virtual-reality-based simulator for diagnostic and therapeutic knee arthroscopy.

Methods The study tests a novel arthroscopic simulator based on passive haptics. Sixty-eight participants were grouped into novices, intermediates, and experts. All participants completed two exercises. In order to establish face validity, all participants filled out a questionnaire concerning different aspects of simulator realism, training capacity, and different statements using a seven-point Likert scale (range 1–7). Construct validity was tested by comparing various simulator metric values between novices and experts.

Results Face validity could be established: overall realism was rated with a mean value of 5.5 points. Global training capacity scored a mean value of 5.9. Participants considered the simulator as useful for procedural training of diagnostic and therapeutic arthroscopy. In the foreign body removal exercise, experts were overall significantly faster in the whole procedure (6 min 24 s vs. 8 min 24 s,

$p < 0.001$), took less time to complete the diagnostic tour (2 min 49 s vs. 3 min 32 s, $p = 0.027$), and had a shorter camera path length (186 vs. 246 cm, $p = 0.006$).

Conclusion The simulator achieved high scores in terms of realism. It was regarded as a useful training tool, which is also capable of differentiating between varying levels of arthroscopic experience. Nevertheless, further improvements of the simulator especially in the field of therapeutic arthroscopy are desirable. In general, the findings support that virtual-reality-based simulation using passive haptics has the potential to complement conventional training of knee arthroscopy skills.

Level of evidence II.

Keywords Education · Simulation · Virtual reality · Knee arthroscopy · Orthopaedic surgery · Passive haptics

Introduction

The training of residents is a very important and demanding mission, especially in the surgical disciplines. Virtual-reality-based training systems have been used in the past for this purpose [4, 23]; it has been reported that they have at least equal value compared with direct observation, animal and/or cadaver models, or videotape learning tools [4, 23]. Example systems have been built and used in various medical disciplines, such as visceral surgery, gynaecology, ophthalmology, or urology [1–4, 7, 13–16, 28, 29, 35]; also in the field of orthopaedics, various attempts have been made, but the actual deployment in the clinics is in general still lacking [5, 6, 10, 17–19, 24, 25, 27, 31, 33, 34, 36]. The vast majority of existing systems employs active haptic feedback devices, while simulators relying on passive stimuli are much less prevalent.

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Our study focuses on the field of knee arthroscopic surgery. Also in this domain, alternatives are sought to support the acquisition of basic surgical principles outside of the operating room [8, 12].

In current practice, mainly plastic and cadaver models are employed to teach adequate skills. Unfortunately, plastic models offer only reduced realism, while using cadavers implies high maintenance requirements and costs. Virtual-reality-based simulators have been explored for some time now as a possible alternative, also for arthroscopy simulators [11, 20, 32, 34].

The main strengths associated with virtual-reality-based simulators are the availability of objective feedback, ease of integration into a training curriculum, and the 24/7 availability for training without any risks for patients. Drawbacks include the limited realism compared with real surgery and the high initial costs in addition to regular service and support expenses.

The evaluation of a new simulator training tool consists first of establishing *face validity*. Secondly, *construct validity* is evaluated [16, 23]. The third step is the evaluation of *skill transfer* from the simulator to the operating room. This step is usually associated with a large long-term study of considerable effort, that is only tackled after face validity and construct validity have been established [23].

The concept of passive haptic feedback which is also used in the tested simulator has been employed earlier in virtual reality environments [4, 21–23, 30]. It has some advantages compared with active force-feedback, in particular the absence of additional mechanisms and actuators, neither inside the knee nor attached to the instrument replicas. In general, this allows us to move the surgical tools as in reality, since they are not mechanically coupled to a haptic interface.

The purpose of the present study is to assess face validity and construct validity of a virtual reality simulator for diagnostic and therapeutic knee arthroscopy employing passive haptics, which was developed in a collaboration between ETH Zurich (Swiss Federal Institute of Technology) and VirtaMed AG, Switzerland.

The strategy followed in this study is the analysis of simulator metrics of participants with varying experience in arthroscopy, as well as the analysis of standardized questionnaires, which were filled out by the same participants. This design follows the established strategies in the field. The following statements were hypothesized:

1. The participants consider the presented two exercises as a realistic representation of a real knee arthroscopy for different aspects of the simulation.
2. The participants believe that the arthroscopy simulator is a useful tool and would recommend it to orthopaedic residents.

3. The knee arthroscopy simulator can discriminate between experts and novices in various measured metrics for the two exercises.

Materials and methods

The system consists of a plastic knee replica fixed to a stand and a computer including a screen. The knee replica corresponds to a standard box model, comprising rigid plastic models of both the femoral and the tibial bone, and rubber replicas of the anterior and posterior cruciate ligament and of the lateral ligaments. The joint interior is covered with a rubber skin with preset portals. The instrument replicas correspond to standard surgical instruments, which are connected by cables to the simulator. The endoscopic image is virtually generated and can feature a number of anatomies, pathologies, and complications.

Participants

Participants ($N = 68$) of an international arthroscopy course held in and from our clinic were grouped into novices ($N = 33$, <20 knee arthroscopies (KA) performed), intermediates ($N = 19$, 21–99 KA), and experts ($N = 16$, >100 KA). Note that a minimum of 100 arthroscopies is requested to complete the specialization in orthopaedic surgery according to the logbook of the national medical board in our country. Therefore, participants having performed more than 100 interventions were defined as “experts”.

Protocol

The informed consent form was signed by all participants. Subjects were informed that data were acquired for the general goal of a validation study. The exact computer-based metrics were not explained. Participants underwent a standardized introduction to the simulator including a video explaining the exercises in detail, followed by 1 min of hands-on time to get familiar with the system. The participants then removed the endoscopic camera and all other tools from the knee.

The first exercise began when the knee was entered again with the camera, at which stage an internal timer started. The first task comprised first a complete diagnostic knee arthroscopy including the visualization of suprapatellar pouch, patella, trochlea, lateral compartment with entire meniscus and popliteus tendon, the medial compartment with entire meniscus, and the central pillar with posterior and anterior cruciate ligament. After the participants claimed to have completed the diagnostic knee

arthroscopy, the removal of five foreign bodies using a grasper was performed. In our study, we discriminated between a diagnostic and a therapeutic procedure time. The former was counted from the point when the knee was entered with the camera until the grasper was inserted via the medial portal. The latter was taken from entering the grasper until either all foreign bodies were removed or a total time of 600 s was exceeded. The order of removal of the foreign bodies was up to the participants. The objects were located in the suprapatellar pouch, in the medial compartment near the anterior meniscal horn and at the root of the posterior horn, in the lateral compartment close to the pars intermedia, and in the posterior horn of the lateral meniscus. The location of the stars was not known to the participants beforehand.

The second exercise consisted of the resection of a radial lateral tear of the meniscus in the pars intermedia using a punch and/or shaver. The desired optimal resection area was displayed coloured in the simulation. The goal was to achieve a perfect partial resection cutting out the whole coloured part. The exercise was completed either when a participant was satisfied with the performed resection or after a maximum time of 360 s. Time was taken again from the moment a participant entered the knee with the camera. In the introduction video, the location of the lesion in the pars intermedia was already stated. Participants were informed that the goal was to resect the coloured part. Whether they wanted to enter the knee through the lateral or the medial portal was up to them. The covered distances of the camera and the tools were accumulated as long as the respective instrument was inside the knee.

Questionnaire

The questionnaire inquired about gender, dexterity, experience in the orthopaedic field, and prior exposure to surgical simulators in general. The latter question mainly related to previously attended skills training courses or other educational programmes regarding surgery. Further, the questionnaire asked for the assessment of the simulator regarding *realism*, *training* capability, and *statements* on the system. For this, the widely used Likert scale is employed. Usually, five-, seven-, or ten-point scales are used. Our questionnaire followed a seven-point Likert scale to evaluate the realism and training capacity. The questionnaire included fourteen questions to assess the realism of the simulation: from “1—absolutely not realistic” to “7—absolutely realistic”. Seven further questions concerned the usefulness of the simulation with regard to training, also rated on a seven-point Likert scale, ranging from “1—fully disagree” to “7—fully agree”. Finally, participants answered eight verbal *agree-disagree* statements concerning training with the simulator.

Face validity

Face validity was assessed using the questionnaires after the participants had finished the two exercises, following established procedures in former validation studies in endoscopic surgery [1–5, 7, 9, 13–16, 27–29, 35]. A point of discussion is the threshold when face validity is demonstrated. Following similar work in surgical training simulators, we considered a rating for realism and training capacity of 5 out of 7 (71 %) as acceptable. This is for instance in line with [34] where a score of seven on a 10-point rating scale (70 %) is considered sufficient.

Construct validity

Prior to studying construct validity, a power calculation for the null hypothesis (“performance of experts is equal to that of novices”) with an acceptable significance (type 1 error, $\alpha = 0.05$) and acceptable type 2 error ($\beta = 0.20$, power = 0.8) was performed. For the power calculation, we used data for intervention time from a previous simulator pilot study (operation time 300 s, standard deviation 105 s). We considered a 20 % reduction in intervention time as a relevant difference. This resulted in a minimum number of 12 subjects in each group, which is in line with previously reported validation studies using similar set-ups [5, 6, 10, 17–19, 24–27, 31, 33, 34, 36]. Sixteen experts, 19 intermediates, and 33 novices were finally recruited at the training course.

IRB approval

All participants gave written informed consent that their blinded information could be used for research. Formal exemption of the institutional review board had been obtained.

Statistical analysis

The statistical analysis was conducted using the Statistical Package for the Social Sciences (SPSS) version 20 for Mac (SPSS Inc., Chicago, IL, USA). A Kruskal–Wallis test has been performed for all metrics. In the case of significant results, pair-wise comparison of the different groups has been carried out with the two-sided Mann–Whitney *U* test to check for significant differences ($p < 0.05$ considered as significant).

Results

The average age of all 68 participants was 35 years [range 27–64; standard deviation (SD) 8], including 20 females

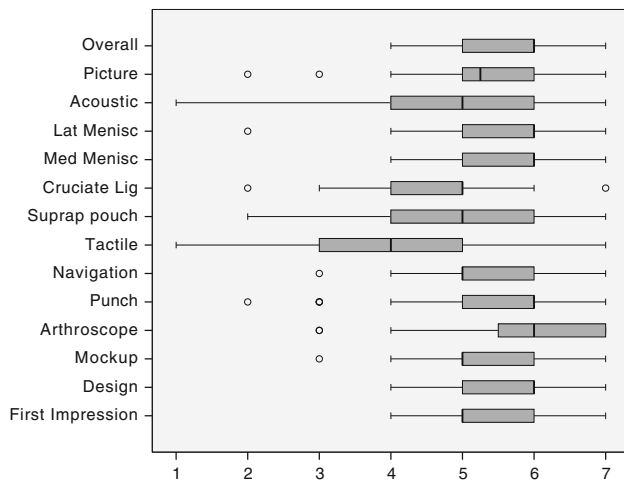


Fig. 1 The part regarding realism included fourteen questions. *Overall* overall impression of how realistic the simulator is found, *Picture* how realistic is the picture in the computer screen, *Acoustic* how realistic are the acoustic sounds while performing an arthroscopy, *Lat Menisc* lateral meniscus, *Med Menisc* medial meniscus, *Cruciate Lig* anterior and posterior cruciate ligaments, *Suprap pouch* suprapatellar recessus, *Tactile* realism of the tactile sensation, *Navigation* how realistic is the navigation in the knee simulator, *Punch* how realistic the punch behaves, *Arthroscope* realism of the arthroscope during the simulated arthroscopy, *Mock-up* how realistic is the mock-up knee model, *Design* how realistic is the design of the whole simulator, *First impression* how realistic is the first impression

and 48 males (29 and 71 %, respectively). The group of novices consisted of 33 residents with an average age of 30 years (range 27–38; SD 3). The intermediate one comprised 14 residents (with more than 3 years of experience) and five registrars (=residents with passed board exam) with an average age of 33 years (range 28–38; SD 3). The expert group consisted of six older registrars and 10 heads of orthopaedic divisions or private practicing orthopaedic surgeons with an average age of 48 years (range 36–64; SD 9). Seven participants were left-handed, two participants were ambidextrous (all three in the expert group), and the remaining 59 participants were right-handed. All questionnaires were filled out, with an exception of 11 missing ages (three in the expert group, three in the intermediate group, and five in the novice group).

Face validity

The first part of the questionnaire concerned the realism of the simulator. Figure 1 illustrates the provided replies on the seven-point Likert scales as box-plots. The arthroscope adaptation was rated best with an average reality score of 5.9, while the tactile sensation was rated lowest with an average score of 3.9 and therefore was below the five-point threshold. Overall, the realism was judged as good with most of the scores between 5 and 6. One parameter (tactile

sensation) was significantly higher for the experts than for the novices ($p < 0.05$). The second part focused on the training potential. The obtained results are presented in a similar fashion in Fig. 2.

Statements

The statements are summarized in Table 1 and Fig. 3.

Construct validity

Construct validity was established with significant differences in several metrics based on the data of the 16 experts, 19 intermediates, and 33 novices. Both the data of the diagnostic knee arthroscopy with foreign body removal (Table 2) and the therapeutic lateral partial meniscectomy were analysed (Table 3).

In the first exercise, 12 participants (36 %) of the novice group were unable to remove all five stars in the given 10 min. Also, two members of the intermediate group (11 %) and two of the expert group (13 %) did not complete the task in the allotted time.

In the second exercise, two participants (6 %) of the novice group were not able to finish the partial meniscectomy, whereas all experts were able to complete it.

Discussion

The most important finding of the present study is that the presented virtual reality simulator showed in general a high acceptance. It also demonstrated the ability to discriminate reliably between different levels of surgical experience (experts and novices). Face validity and construct validity could be established, which is the first step in the simulator validation chain [8, 9, 12, 23]; it showed promising scores in the reality and training categories. The judgement of face validity by novices is a controversial issue in the literature, and in some studies, the authors decide to incorporate expert opinion only [11, 20, 32, 34]. However, in contrast, the novices in this study are not medical students, but residents in orthopaedic or trauma centres where they frequently assist in knee arthroscopy. We did not question how many knee arthroscopies they have assisted but believe it is allowed to assume that the novices have assisted enough to evaluate this simulator. In addition, the questionnaire includes questions not only regarding realism, but also regarding the training capacity of the simulator. For a successful integration of simulators in a training curriculum, both trainers and trainees need to be convinced of its value. Therefore, in this study, it was decided to include novice, intermediate, and expert opinions and compare the answers statistically. The differences

Fig. 2 This part of the questionnaire included seven questions. Overall, the participants judged the training capacity with a mean score of 5.9. The lowest mean score resulted for the therapeutic training and the highest for the “hand-eye” training capacity. There were no significant differences between the groups

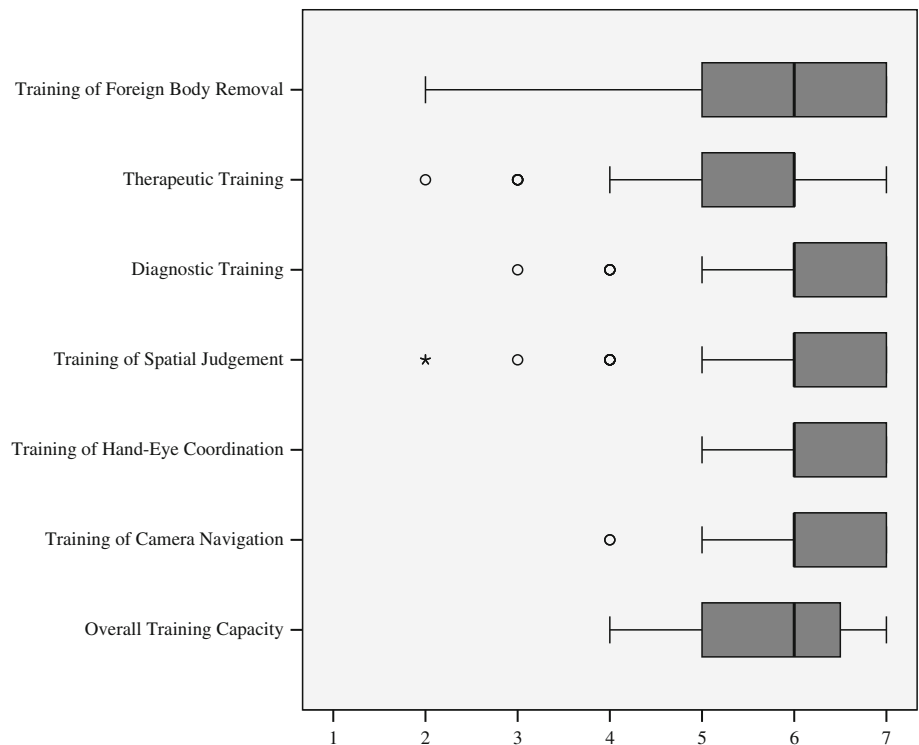


Table 1 Agree–disagree–undecided statements concerning the simulator system of the face validity study

1. The arthroscopy simulator is useful for procedural training of diagnostic and therapeutic arthroscopy
2. I would recommend this arthroscopy simulator to my colleagues
3. The arthroscopy simulator training should be offered to all novices for pre-training before performing surgery on real patients
4. The arthroscopy simulator training should be recommended for any orthopaedic resident to improve his/her skills individually
5. I would like to have this arthroscopy simulator in my institution
6. The arthroscopy simulator training should be obligatory for pre-training novices before performing surgery on real patients
7. The arthroscopy simulator training should be integrated into the current curriculum (board exam) of the specialization programme of orthopaedic surgeons
8. There are certain disadvantages in this arthroscopy simulator training method

The results of this section are depicted in Fig. 3

between the answers of the novices and the experts were not significant except regarding the tactile sensation. This was the only parameter ranked significantly lower in the expert group compared with the novice group.

At this point, the key difference between the examined simulator system and other solutions has to be stressed. Other commercially available virtual reality simulators (Toltech Knee Arthroscopy Simulator and ArthroMENTOR) provide tactile sensation through robotic force-

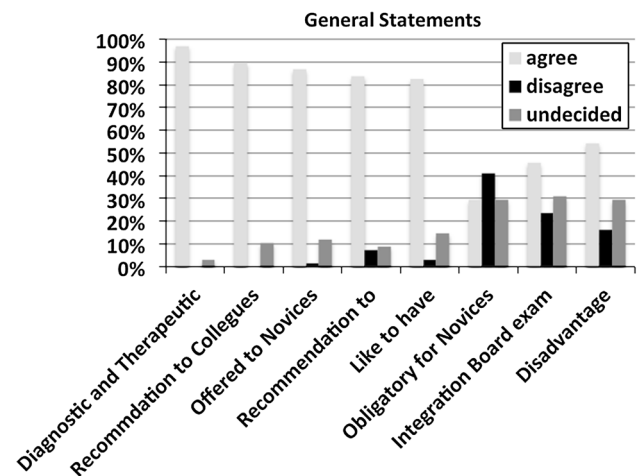


Fig. 3 Percentages of replies to the general statements. The detailed questions which had been asked are stated in Table 1. The x-axis displays abbreviated versions of the statements. The y-axis shows the agree, disagree, and undecided responses of the 68 participants as a percentage

feedback devices (Phantom Omni and Desktop, by Sensable Technologies, Wilmington, MA, USA). In contrast to this, the tested simulator provides the sensation through contact with a plastic structure similar to a Sawbones box model. In such a set-up, two sources of impaired realism of the tactile sensation exist: on the one hand, the anatomical structures in the box model have slightly different mechanical properties than the real ones; on the other hand,

Table 2 Comparison of values obtained for the various metrics between the three groups for the foreign body removal exercise

	Novices (<20 procedures; N = 33)			Intermediates (21–99 procedures; N = 19)			Experts (≥100 procedures; N = 16)			All three groups: Kruskal–Wallis test		
	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median	p value	p value	p value
Total operation time (s)	243	600	513	266	600	436	197	600	358	0.002	n.s.	0.002
Diagnostic time (s)	110	412	202	85	465	173	73	324	162	n.s.	n.s.	n.s.
Removal time (s)	102	466	290	123	410	242	85	451	179	0.022	n.s.	0.009
Camera horizon alignment (s)	0	587	328	0	571	268	108	499	231	n.s.	n.s.	n.s.
Camera off (s)	12.92	600	136	6	600	165	8	381	129	n.s.	n.s.	n.s.
Camera distance (cm)	146	380	254	99	347	195	97	356	167	0.011	0.019	0.011
Grasper distance (cm)	22	453	99	36	239	93	40	175	73	n.s.	n.s.	n.s.

s seconds, cm centimetre, n.s. not significant

Total operation time (s) The total time to complete the first exercise, including the removal of the five stars. After 10 min, the simulation was stopped

Diagnostic time (s) The time from the start until the participants claimed to have seen all the anatomical landmarks to complete a diagnostic arthroscopy

Removal time (s) The time from the moment the participants claimed to have completed the diagnostic arthroscopy until they removed all the five stars, or until the 10 min were over

Camera horizon alignment (s) The time the camera showed the horizon correctly (=horizontally), with a tolerance of ±15°. The ±15° threshold was defined by an expert panel during the development of the simulator

Camera off (s) The operation time minus the camera horizon alignment time where the camera was not correctly held in the horizon with a tolerance of ±15°

Camera distance (cm) The cumulative path the camera took in the total operation time

Grasper distance (cm) The cumulative path the grasper took in the total operation time

For three (total operation time, foreign body removal time only, and cumulative camera distance) out of seven metric parameters, there was a significant difference between the experts and the novices in favour of the experts

^a Mann–Whitney U test (two-sided)

Table 3 Comparison of values obtained for the various metrics between the three groups for the partial meniscectomy exercise

	Novices (<20 procedures; $N = 33$)			Intermediates (21–99 procedures; $N = 19$)			Experts (≥ 100 procedures; $N = 16$)			All three groups: Kruskal– Wallis test p value	Intermediates versus novices ^a p value	Experts versus intermediates ^a p value	Experts versus novices ^a p value
	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median				
Total operation time(s)	103	480	221	88	274	170	87	184	132	<0.001	0.034	0.037	0.000 ^a
Camera distance (cm)	8	122	42	13	77	26	10	56	22	0.002	0.041	n.s.	0.001 ^a
Punch distance (cm)	27	169	66	22	227	54	28	112	44	0.033	n.s.	n.s.	0.006 ^a

s seconds, cm centimetre, n.s. not significant

Total operation time (s) The time from the start of the exercise until a participant decided that he or she was content with the partial resection of the partial tear in the lateral meniscus, or after 6 min

Camera distance (cm) The cumulative path the camera took intra-articularly in the total operation time

Punch distance (cm) The cumulative path the punch took intra-articularly in the total operation time

^a Mann–Whitney U test (two-sided)

mismatch between the structures in the anatomical replica and their virtual counterparts which can originate from impaired motion tracking or poor calibration can lead to inappropriate tactile sensations. Possible solutions for this have recently been proposed in [31]. Nevertheless, the training capability of the tested simulator already received high scores.

With the discrimination between surgeons of different surgical levels, construct validity has been successfully established [23]. The applied parameters, e.g. the measurement of the covered distance allow us to compare the levels and, more importantly, to follow the progress of each user. Albeit, as a caveat, it should be stated that intervention time by itself does not always characterize a better surgeon (i.e. fast does not equal safe). Further, in the partial meniscectomy exercise, being fast and leaving an instable part of the meniscus behind may cause painful meniscal symptoms for the treated patients in real-life situations. Here, the simulator has to provide better metrics and become more precise in discriminating what is safe and provides an optimal outcome for the patient.

Some further shortcomings of the employed simulator version should also be mentioned. One crucial step in arthroscopy is the positioning of the portal. This element is not part of the training since the portals are already provided by the mock-up model. A further point which is not yet simulated is the swelling of Hoffa's fat pad and bleedings, which are both relevant factors making knee arthroscopy more difficult. Another element is the iatrogenic cartilage damage the surgeon leaves in the knee, which is currently not tracked. However, all these

shortcomings will be or have already been addressed in the latest updates of the simulator system.

Further, although the study was designed very carefully, it should be mentioned that face validity is a highly subjective measure and can be influenced by systematic errors. The novelty of the simulator and its presentation during an arthroscopic training course might have influenced the participants to see the simulation in a more favourable light. Moreover, such a setting may cause a selection bias by attracting participants with high interest in medical education. The interpretation of the questionnaire can also differ among the raters, and Likert scales may cause distortions, e.g. by tendencies to avoid using extreme responses in the case of realism and training capacity or by the tendency to agree to statements as presented. Also, not everybody may have been experienced with using the seven-point Likert scale. We tried to minimize the error sources by designing the questionnaire based on an earlier version which was developed with support from a social scientist [3, 16, 23] and by explaining both the questionnaire and the Likert scale verbally.

In summary, the presented study confirmed the three hypotheses. First, the arthroscopy simulator is considered as a realistic representation of a real knee arthroscopy for different aspects of the simulation. Second, the participants considered the arthroscopy simulator as a useful tool and would recommend it to other orthopaedic residents. Third, the simulator can discriminate between experts and novices in various measured metrics for the two exercises.

This study lays the groundwork for future validation studies of the specific arthroscopy simulator based on

passive haptics. In future work, foremost the transfer from simulation to the operation room should be studied. Also, a comparison between the simulator and a cadaver training should be carried out, in order to establish *concurrent validity*. Finally, the question of the economic impact requires further scrutiny in order to justify the investment into virtual reality arthroscopic training.

Conclusion

The presented arthroscopy simulator is a realistic and useful training method with which it is possible to differentiate between different levels of arthroscopic experience. The acceptance of the training system is high, even though only passive haptic feedback is employed. The simulator is regarded as a worthwhile addition to the educational programme of arthroscopic surgeons. Virtual reality simulation could offer a significant contribution to the training of knee arthroscopy skills, but further improvement of the simulator especially in the field of the therapeutic arthroscopy is desirable.

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