Title: Virtual Reality Facilitates Training in the Performance of Total Hip Arthroplasty: A Randomized Controlled Trial

Running title: Virtual Reality Simulation in Total Hip Arthroplasty

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Abstract

Background: Virtual reality (VR) simulation has become an accepted method of training eneral surgery residents, but has been used sparingly in orthopedic surgery residency programs. No study has yet demonstrated efficacy of VR simulation for teaching total hip arthroplasty (THA) to trainees.

Questions/Purposes: In a blinded, randomized, controlled trial among post-graduate year (PGY) 1 orthopedic residents, we asked: (1) Did use of VR simulation improve residents' performance in cadaver total hip arthroplasty? (2) Did use of VR simulation have a preferentially beneficial effect on residents' technical skills, procedural knowledge, anatomic knowledge, or surgical efficiency?

Methods: 14 PGY1 orthopedic residents from a single institution were evaluated for their ability to complete a cadaver THA. All participants completed a pre-test and a single cadaver THA to establish baseline levels of knowledge and surgical ability before being randomized to complete VR-THA simulation. 7 residents completed the VR-THA training in addition to standardized study materials that all 14 participants received. All participants then completed a second cadaver THA and retook the test to assess for score improvements from the established baseline. The primary outcome was improvement in test and cadaver THA scores. No participants were lost to follow up, and there was no missing data for the primary outcome.

Results: No statistically significant difference was seen in the improvement in test scores with respect to the VR and control groups ($p = .078$). In multivariate regression analysis, the VR cohort demonstrated a significant improvement in cadaver THA scores compared to the control cohort ($p = .048$). The VR cohort demonstrated greater improvement in all score categories (procedural steps, technical performance, visuospatial skills, efficiency, and flow) compared to the standard group, but this trend was only statistically significant for technical performance ($p = .009$).

Conclusions: Use of VR-simulation led to an improvement in PGY1 resident scores on cadaver THA. The most significant improvement was seen in technical skills, and there were no significant difference seen in test score improvement between the VR and control groups. We anticipate that VR simulation will become an indispensable part of the orthopedic surgical education, but further study is needed to determine how best to use VR simulation within a comprehensive curriculum.

Level of Evidence: Level 1

Introduction

Leading educators in surgical disciplines have recognized that the traditional apprenticeship model of teaching may not sufficiently prepare current trainees for clinical practice. This is especially true given widespread concerns about patient safety, operating room (OR) efficiency, and resident work hour restrictions [7,20]. Surgical skills are not ideally acquired by observing and assisting alone [1,26], and, as a result, the quality of surgical trainee education may suffer.

In 2012, the American Board of Orthopaedic Surgery (ABOS), and the Residency Review Committee (RRC) for Orthopaedic Surgery, developed new training program recommendations [8,27] to standardize and improve residency curricula through use of quantifiable metrics and competency-based training, which may involve simulation as a means of augmenting OR training. The training exercises were designed to prioritize affordable, low-tech options [28] such that complex procedures were simplified into focused, modular exercises. Both the orthopedic and general surgery literature have demonstrated accelerated acquisition of highly specific skillsets, an improved understanding of surgical instrumentation, and improved trainee confidence with surgical residency "bootcamps" [10,20,27]. However, these modules fail to consolidate and reproduce the complex thought process and skills needed to perform a safe and expeditious surgery.

Virtual reality (VR) has emerged as a low-cost, highly accessible consumer product, and training on simulators has become standard in industries such as aviation. Combined with the continued rapid advancements in graphic processor technology and interest from software developers to create immersive surgical skill training simulations, VR users can practice surgical skills in an interactive and risk-free virtual environment. Other surgical disciplines, including general surgery, neurosurgery and otolaryngology, have demonstrated positive results with the use of VR in resident training, as well as preoperative planning [3,15,21,25]. Simulation in orthopedic surgery has focused primarily on arthroscopy [2], likely due to the procedural and instrumentational complexity involved with creating a realistic simulated open procedure, such as total joint arthroplasty (TJA). With recent advances in VR technology, VR simulation software is becoming more accessible in orthopedic surgery [6, 19, 32]. It is particularly attractive as a supplemental training method for TJA, as it obviates the need for lab space and multiple instrument trays.

To date, there has not been a study assessing the utility of VR simulation for learning operative skills in TJA. The objective of this study is to evaluate the utility of VR simulated total hip arthroplasty (THA) in providing targeted surgical training for orthopedic trainees. Specifically, this study will evaluate improvement in surgical skill, knowledge, and We anticipate that the life-like engagement of the VR simulation will make it easier to connect the training directly to the surgical procedure, allowing earlier progress and proficiency in the operating room.

Methods

This study was a prospective randomized controlled trial. Institutional Review Board (IRB) approval was received prior to the initiation of this study. Eligible study participants included all fourteen incoming PGY-1 orthopedic surgery residents at our large tertiary university academic center. Exclusion criteria included any PGY-1 resident unwilling to participate. One week prior to the planned baseline cadaveric THA surgery session, all eligible participants were invited to an information session regarding the study and voluntarily enrolled. PGY-1 residents were specifically chosen for participation because they are surgically naïve, and therefore less likely than senior residents to have had disparate training experiences in the OR based on their personal interests. Additionally, we felt that junior residents were most likely to benefit from training focused on the procedural steps of THA.

Pretest

Immediately after enrollment, PGY-1 residents were asked to complete a multiple-choice pre-test assessment to quantify their baseline medical and procedural knowledge of hip arthritis and THA (Appendix 1). The pre-test assessment form was developed with a specific focus on the pathophysiology of arthritis, surgical indications, anatomy, approaches, and radiographic imaging, as these are areas of interest in the Accreditation Council of Graduate Medical Education (ACGME) Orthopaedic Surgery Milestones Report Worksheet for hip and knee arthritis (Appendix 2). All participants were unaware of this study prior to enrollment and were therefore unable to prepare for the pre-test assessment, which allowed us to use test scores as an accurate representation of baseline knowledge. No restrictions were imposed on participants during the 2 weeks between the pre-test and the baseline cadaveric THA session; all trainees chose to prepare as much or as little for surgeries as they saw fit. During this two week period, trainees had not yet been randomized the VR simulation group or to the control group.

Cadaveric THA – Session 1

All 14 study participants performed a cadaveric THA through a standard posterolateral approach at our institution's surgical simulation center to assess the baseline surgical skills of each trainee. Pelvis to toe cadavers were positioned on peg boards and draped by senior orthopedic residents. Cadavers were specifically selected to exclude from use any specimens with prior hip fracture, prior hip surgery, inflammatory arthritis, morbid obesity > BMI 40 kg/m^2, neuromuscular disease, and congenital abnormalities of proximal femur, acetabulum, or pelvis. Surgical instrumentation utilized in this study included the Synergy stem and R3 acetabular component system (Smith & Nephew, Memphis, TN), Stryker (Mahwah, NJ) Series 7 sagittal saw, as well as our institution's standardized trays of THA instruments. These systems were chosen because they are most commonly used at our institution.

Study participants were designated as the primary surgeon for each cadaveric THA surgery. A PGY-4 or PGY-5 orthopedic resident pursuing fellowship training in hip and knee arthroplasty served as first assist. Additional assistance was provided by medical students. First assists were instructed to guide study participants with prompting questions, and intervene only if:

1) Study participants requested assistance to progress to the next step
2) Study participants were unable to progress through the surgery

3) Study participants committed or were at risk to commit a critical error (Appendix 3) that would impede further surgical progress

Surgical competency was evaluated using a novel checklist adapted from a combination of the "Patient Care" portion of the ACGME Milestones curriculum for hip and knee arthritis [31], operative checklist from the University of Toronto "Complex Total Hip Arthroplasty Perioperative Checklist"[12], and part of the Royal Canadian College of Physicians and Surgeons' competency-based curriculum [4] (Appendix 4). Scoring of each step was based on the Ottawa Surgical Competency Operating Room Evaluation (O-Score) scale [13]. Global assessment questions also adapted from the O-Score about each participant's knowledge of specific procedural stems, technical performance, visuospatial skills, efficiency, and flow were recorded after each session. Scoring began from the moment study participants began planning surgical incision and ended after stability testing and leg length checks were complete. Checklist evaluations were completed by four high volume, fellowship-trained, arthroplasty surgeons at our institution (W.B.M., W.J.L., R.S., L.P.). All evaluators scored only one study participant at a time.

Randomization

Immediately after the baseline cadaveric session, participants were randomized to one of the two cohorts by a computerized random number generator: VR-THA + standard study materials (VR group) versus standard study materials (standard group) only. Participants were privately notified of their randomization by e-mail, and were asked not to disclose their designated cohort with any other study participant or research personnel. Only two members of the research team (D.W. and J.E.F.) were aware of the cohort assignments during this study. They played no role in data analysis and were instructed to keep the other study personnel blinded to the identity of the participant group make-up. All participants were provided standardized THA study material consisting of a book chapter on primary total hip arthroplasty [23], an article on THA templating [14], and an article on soft tissue balancing of the hip [9].

VR Surgical Simulation

Participants randomized to the VR group were required to complete 2 VR simulated THAs. Prior to the VR THA, participants were asked to complete a REDCap (Nashville, TN) survey. This survey evaluated the study participant's previous experience with video games and VR technology, as well as quantify the level of interest and anticipated utility of VR technology in surgical skills training (Appendix 5). All surveys were administered by D.W. and J.E.F. to ensure blinding of all other study personnel VR THA simulations were then performed using the ORamaVR (Heraklion, Crete, Greece) software and the Oculus Rift CV1 (Menlo Park, CA) headset and hand controllers. Each participant completed two tries at VR THA. Metrics collected by the VR software from these sessions were total amount of time spent and time per trial THA.

Upon completion of their VR THA, participants were provided a REDCap exit survey (Appendix 6), which focused on their interest in using VR simulations for surgical skills training, as well as assessing for potential negative consequences (e.g. nausea, motion sickness, etc.).

Cadaveric THA – Session 2

All study participants returned to the surgical simulation center 2 weeks after the first cadaveric THA session. Cadaveric THAs were performed in an identical manner using new cadavers. Participants were also asked to complete a post-text exit exam that was identical to their pre-test exam immediately after their cadaveric THA.

Power Analysis

As this is the first study of its kind, we did not have a precedent from which to base power calculations. Precursory power analyses using an α=0.05, β=0.05 (power = 95%) and an anticipated mean milestone score improvement of 0.5 with a standard deviation of 0.25, indicate that the required total sample size for this study is 12.

Statistical Analysis

The change in pre- and post-test scores between the VR and control cohorts was defined as a primary outcome. The change in first and second cadaver THA scores between the VR and control cohorts was defined as a primary outcomes. The changes in global assessment scores from the first and second cadaver THA sessions were defined as secondary outcomes.

T-tests and Mann-Whitney U tests were conducted to assess whether there was a significant difference between exit and baseline quiz scores, first and second cadaver session scores, and among the specific aspects of the scoring tool global assessment (primary and secondary outcomes). Because the cadaver sessions were scored by four different surgeons, a multivariate linear regression analysis was conducted to account for grader variability. The methodologic quality of our study was assessed using the 22-point Consolidated Standards of Reporting Trials (CONSORT) checklist [29].

Results

_______Fourteen PGY1 residents were enrolled in the study and completed all activities without attrition. The mean age of participants was 28.3 years (range 25-33), 9 males, and 5 females. The VR group demonstrated greater improvement on quiz scores compared to the standard group, however this finding was not statistically significant (p = .078) (Table 1).

Using our assessment tool, a perfect score was defined as 240, representing a procedural score of 220 and a global score of 20, which represents complete independence in every step of a THA. There were no significant differences identified between the two cohorts with respect to mean pre-test and first cadaver session scores (Table 2). In simple linear regression analysis of VR training on the difference in cadaver assessment scores, there were no significant differences identified (p = .386) (Table 3). Examination of raw scores demonstrated a disparity in the strictness of scoring among the four graders. A second analysis was conducted to assess the graders' impact on score differences, which was statistically significant (Table 4). In multivariate regression of performance during cadaver sessions, which controls for the effect different graders may have on scoring, the VR group improved their scores by approximately 18 points, which was significantly better than the improvement demonstrated by participants in the standard group ($p = .048$). Table 5 controls for grader variation independently between session 1 and session 2 (Table 5). When considering the global assessment aspect of the cadaver sessions in multivariate regression, the VR group demonstrated greater improvement in all score categories (procedural steps, technical performance, visuospatial skills, efficiency, and flow) compared to the standard group, but this trend was only statistically significant for technical performance ($p = .009$) (Table 6).

The seven participants who were randomized to VR training each answered questions on their familiarity with video games and VR, and their opinion of the utility of VR for surgical training (Table 7). 3 of 7 (42.9%) reported experience with video games, while only 1 participant reported regularly playing video games. Each participant then completed two VR THAs. The mean amount of time spent doing VR simulation was 40:49 (range 27:29-50:33, ± 7.56. All seven participants felt VR would be at least "mildly helpful" in surgical training. The participants who reported familiarity with video games were not any more or less likely to perceive VR to be a helpful learning tool; one rated it "very helpful," another rated it "helpful," and the third rated it "mildly helpful," indicating that familiarity with video games is not related to a positive perception of the usefulness of VR simulation.

Discussion

The results of our study demonstrate that use of VR-THA simulation helped beginning trainees improve their surgical skills. All graders were consistent in the severity of their scoring among participants, the change in the statistical significance of trainee improvement in THA ability after VR training indicates that the stricter graders scored a large portion of the VR-trained residents. Trainee assignment to grader was completely random and not based on VR randomization status. When the grader effect is removed from the difference in scoring attributed to VR and control groups, the VR group improves over the control group. The participants' technical performance, which involves efficient performance of steps, avoiding pitfalls, and respecting soft tissues, improved after VR training. These results are supported by the findings of a 2016 meta-analysis on the effectiveness of VR in arthroscopy, which demonstrated a significant improvement in technical skills [2]. In our study, VR training did not have a significant effect on the participants' medical and procedural knowledge of arthritis and THA, as evidenced by performance on the written quiz. This is not entirely surprising, as the VR THA simulation program does not prompt the user with any recall or comprehension questions. Our results indicate that VR simulation may be a useful adjunct for teaching technical skills to beginning residents, but, in its current form, it likely cannot replace the teaching utility of reading or live OR repetitions.

As the most successful surgical procedure of the 20^{th} century, THA has changed the international landscape of orthopedic surgery. From the beginning, Sir John Charnley demonstrated that high-quality research and the responsibility to train young orthopedic surgeons enhances the senior surgeon's ability to achieve the highest quality care and maintain patient safety [11]. In recent years, we have seen the Hip Society, the Knee Society, and the American Association of Hip and Knee Surgeon (AAHKS) champion multiple initiatives to improve the safety profile for patients undergoing TJA. We believe that advancing surgical skills training and simulation is the next frontier.

Surgery is a technical and learned skill, and achieving expert level in surgery requires acquiring complex skills such as superior pattern recognition, use of forward and backward reasoning within a highly structured knowledge base, self-monitoring, and minimal distractibility [22]. If we consider about 75% of the important events in an operation to be related to decision making, and 25% to be related to dexterity [30], no simulation will replace the live OR as a place to learn judgement and finer technical points of an operation from a master surgeon. However, the OR may not be the best place to learn surgical skill, due to numerous distractions often related to patient safety issues, time constraints, inconsistent teaching ability of the surgical mentor, or lack of opportunity to prepare due to other clinical duties [16]. Technical execution is necessary for successful completion of any operation, but perhaps mastering basic technical skills early on in a lower-risk setting removes some of the stress from the OR environment and allows trainees to focus on developing surgical judgement.

Multiple studies from the general surgery literature have shown that simulation has improved resident performance in the OR [5]. VR laparoscopic training has been studied since the early 2000s, with comparable improvement in skills seen in trainees who use VR simulators compared to those using standard trainers [18]. A randomized study of trainee performance after use of VR trainers for laparoscopic cholecystectomy demonstrated that use of VR simulation significantly improved trainee OR performance [28]. In orthopedic surgery, the transferability to the OR of technical skills acquired in VR simulation has yet to be defined, though it has been established in general surgery [24,28].

Based on our results, and several published studies assessing VR simulation for arthroscopy, it is clear that VR simulation confers technical benefit to orthopedic surgical trainees. Our study is the first to look at the utility of VR simulation for teaching THA to trainees, and our results indicate that it has the potential to make an impact on THA education. VR helps trainees to become familiar with the three-dimensional anatomy and instrumentation used to perform the operation without the lab space and instrument trays required for traditional simulation. Our current challenge is to determine how best to use VR simulation for the education of trainees at every level. As VR software technology continues to improve, the potential for increased procedural complexity and varying applications of the technology will increase. For example, for more senior trainees, it may be helpful to simulate periprosthetic fractures, revision hip arthroplasty, or hip dysplasia. Junior residents may benefit more a simulated anatomy lab, to allow them to focus on a particular aspect of the procedure to improve, such as exposure of the acetabulum, rather than trying to get through the entire procedure at once.

A limitation of this study is the small sample size, which limits our ability to generalize our results. Though our study was sufficiently powered to achieve statistical significance, a sample size of seven in each cohort is small enough for particular trainees (such as those with greater aptitude) to be grouped together even after randomization. However, our residency program has the largest class in the nation, and at a single center, it would not be possible to get more participants of the same level in each group. One of the reasons why PGY1 residents were selected for participation is that they are surgically naïve, and therefore least likely to have had disparate training in the OR based on their personal experiences. The score from the first cadaver session was used to establish a baseline skill level for each participant, from which improvement in surgical ability, rather than raw score, could be measured.

Another limitation was the variability among graders, which suggests that, even though a significant difference in scores by group was detected, the underlying measures may be somewhat subjective. We made all possible attempts to make the grading process as rigorous as possible, using only validated scoring tools to build our score sheet [4,12,13,31]. Additionally, the use of multiple graders is more realistic, as residents normally receive evaluations from multiple faculty members, who may not all agree on the resident's surgical abilities. Multivariate analysis was used to statistically account for these inconsistencies.

Conclusion

VR simulation will become a useful tool for improving skills in total hip arthroplasty, especially as software platforms continue to improve. All participants in our study expressed interest in the continued use of VR simulation as a teaching tool, regardless of their prior familiarity with video games. We continue to work towards a comprehensive curriculum, integrating written material, VR simulation, and live OR learning, to teach orthopedic residents the necessary technical and decision-making skills. We anticipate that VR simulation will become an indispensable part of the orthopedic surgical education, and believe that this technology will train and inspire the next generation of hip arthroplasty surgeons.

Level of Evidence: Level I, Randomized Controlled Study.

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Tables

Table 1. Difference in quiz scores by group as indicated by T-tests, mean (SD)

VR Group	Baseline Quiz	Exit Quiz	Score Difference	p-value
Total (n=14)	9.1 (1.5)	11.6 (2.7)	2.4 (2.9)	0.008
Control (n=7)	9.7 (1.8)	12.0 (2.5)	2.3 (2.8)	0.070
VR Group (n=7)	8.6 (1.0)	11.1 (3.1)	2.6 (3.2)	0.078

Table 2. Difference in cadaver session scores by group, as indicated by T-tests, mean(SD)

VR Group	Session 1	Session 2	Difference	p-value
Total (n=14)	76.9 (14.1)	91.9 (24.6)	14.9 (27.9)	0.066
Control (n=7)	74.7 (12.9)	93.3 (23.4)	18.6 (25.2)	0.099
VR Group (n=7)	79.1 (15.9)	90.4 (27.6)	11.3 (31.9)	0.386

Table 3. Simple regression of difference in cadaver session scores by VR training and grader

Variable	β Coefficient (95% CI)	p-value
VR Training	-7.3 (-40.8, 26.2)	0.644
Grader Session 1		
W.J.L. (ref)	---	---
W.B.M	23.5 (-7.3, 54.3)	0.122
Grader Session 2		
L.P. (ref)	---	---
R.S.	-41.0 (-62.8, -19.2)	< 0.001

Table 4. Multivariable linear regression of the difference in score of cadaver session 2 from cadaver session 1 predicted by VR training and grader.

Variable	β Coefficient (95% CI)	p-value
VR Training	18.6 (0.2, 37.0)	0.048
Grader Session 1		
W.J.L (ref)	---	---
W.B.M.	34.3 (15.9, 52.7)	0.002
Grader Session 2		
L.P. (ref)	---	---
R.S.	-43.7 (-58.7, -28.6)	< 0.001

Table 5. Multivariable linear regression of the difference in technical performance score of session 2 from session 1 predicted by VR training and grader.

Variable	β Coefficient (95% CI)	p-value
VR Training	0.84 (0.26, 1.41)	0.009
Grader Session 1		
W.J.L. (ref)	---	---
W.B.M.	1.36 (0.79, 1.94)	< 0.001
Grader Session 2		

L.P. (ref)	---	---
R.S.	-1.41 (-1.87, -0.94)	< 0.001

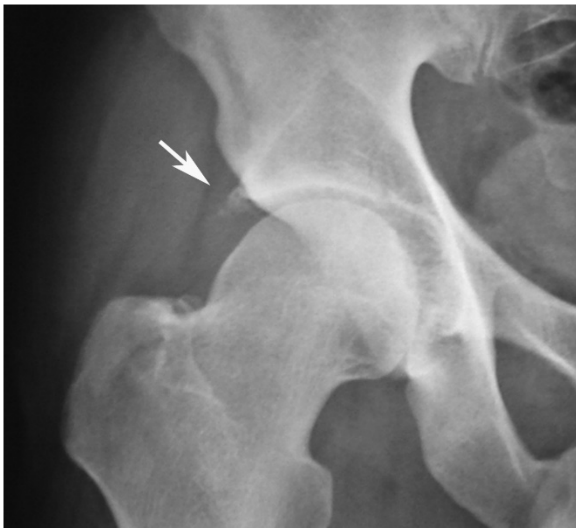
Table 6. Participant description of video game familiarity and VR experience and perspective.

Participant	Gender	Prior Video Game Experience	Regularly Plays Video Games	Perception of Utility of VR Session on Surgical Development	Time Spent VR Training (mm:ss)
1	Female	Yes	No	Very Helpful	42:26
2	Female	No	No	Helpful	50:33
3	Male	Yes	Yes	Helpful	27:29
4	Male	No	No	Very Helpful	42:23
5	Female	No	No	Helpful	42:23
6	Female	Yes	No	Mildly Helpful	38:36
7	Male	No	No	Mildly Helpful	41:54
Totals counts and mean time	4 (57.1%) Female 3 (42.9%) Male	3 (42.9%)	1 (14.3%)	2 (28.6%) Mildly Helpful 3 (42.9%) Helpful 2 (28.6%) Very Helpful	40:49

Appendix 1. Medical Knowledge – Total Hip Arthroplasty

1. Nonoperative management of hip arthritis includes:
    a. NSAIDs
    b. Tramadol
    c. Walking sticks
    d. Weight loss
    e. Corticosteroid injections
    f. All of the above
2. Osteoarthritis is due to:
    a. Mendelian inheritance
    b. Vitamin D deficiency
    c. Autoimmune/Connective Tissue Disease
    d. Articular cartilage damage with progressive degeneration
3. Inflammation in osteoarthritis:
    a. Occurs in the articular cartilage of the hip joint
    b. Occurs in the synovium
    c. Occurs both in the articular cartilage and synovium
    d. Does not occur in osteoarthritis
4. The hip joint allows motion in different anatomic planes. How many degrees of freedom does the hip joint provide and in which anatomic planes?
    a. 2 degrees of freedom in compression and tension
    b. 2 degrees of freedom in flexion and extension
    c. 3 degrees of freedom in flexion-extension, abduction-adduction, and axial rotation
    d. 3 degrees of freedom in anterior-posterior translation, medial-lateral translation, and axial motion
    e. 6 degrees of freedom in flexion-extension, abduction-adduction, axial rotation, anterior-posterior translation, medial-lateral translation, and axial motion
5. In patients with a Trendelenburg gait, which of the following gait patterns is exhibited?
    a. The pelvis on the swing side drops, causing increased adduction of the affected hip during the stance phase
    b. The pelvis on the swing side drops, causing decreased adduction of the affected hip during the stance phase.
    c. The pelvis on the swing side elevates, causing increased adduction of the affected hip during the stance phase
    d. The pelvis on the stance side elevates, causing decreased adduction of the affected hip during the stance phase
    e. The pelvis on the swing side remains neutral, but there is circumduction of the affected hip
6. Patients display a Trendelenburg gait to compensate for weakness in which of the following muscle groups?
    a. Hip adductors
    b. Hip abductors
    c. Hip flexors
    d. Knee extensors
    e. Hip extensors

7. Use of a cane held in the contralateral hand reduces joint reactive forces through the affected hip by approximately 50% by which of the following mechanisms?
    a. Reducing hip abductor muscle pull
    b. Increasing hip flexor muscle pull
    c. Moving the center of rotation for the femoroacetabular joint
    d. Increasing joint congruence at the femoroacetabular joint
    e. Moving the center of gravity posterior to the second sacral vertebra



A

B

C

D

8. Match the image with the pathology:
    a. Femoral Acetabular Impingement
    b. Rheumatoid Arthritis
    c. Osteoarthritis
    d. Avascular Necrosis

Procedural

9. Incision of the skin in the posterior approach should be:
    a. Along the anterior aspect of the greater trochanter/femur
    b. In line with the middle of the greater trochanter/femur
    c. Along the posterior aspect of the greater trochanter/femur
    d. From the posterior aspect of the greater trochanter, and angling anteriorly towards the anterior aspect of the proximal femur
    e. From the anterior aspect of the greater trochanter, and angling posteriorly towards the anterior aspect of the proximal femur
10. When detaching the short external rotators from their femoral insertion, the hip should be:
    a. Internally rotated
    b. Externally rotated
    c. Internally rotated and flexed
    d. Externally rotated and flexed
    e. Internally rotated, adducted and flexed
    f. Externally rotated, adducted and flexed
    g. Internally rotated, abducted and flexed
    h. Externally rotated, abducted and flexed
11. What is the purpose of moving the hip in the manner described in question 2: (Choose all that apply)
    a. Improving visibility of the short external rotators
    b. Moving the operative field to protect the femoral sheath
    c. Moving the operative field to protect the gluteal nerves
    d. Moving the operative field to protect the sciatic nerve
    e. Improve hemostasis
12. Dislocation of the femoral head is performed by:
    a. Internally rotated
    b. Externally rotated
    c. Internally rotated and flexed
    d. Externally rotated and flexed
    e. Internally rotated, adducted and flexed
    f. Externally rotated, adducted and flexed
    g. Internally rotated, abducted and flexed
    h. Externally rotated, abducted and flexed
13. Which of the following maneuvers places the obturator artery at greatest risk during a total hip arthroplasty?
    a. Placement of a posterior retractor along the posterior wall
    b. Placement of an acetabular screw in the posterior-superior quadrant
    c. Placement of an inferior retractor under the transverse acetabular ligament
    d. Placement of an acetabular screw in the anterior-superior quadrant
    e. Placement of an anterior retractor along the anterior wall
14. Prior to reaming, what must be performed first: (Choose all that apply)
    a. Acetabular component positioning
    b. Capsulotomy

   c. Labrum takedown
   d. Osteophyte removal
   e. Screw placement
   f. Soft tissue removal
15. Hip reaming should occur in what order:
   a. Medially then inferiorly
   b. Medially then superiorly
   c. Medially then anteriorly
   d. Medially then posteriorly
   e. Inferiorly then medially
   f. Superiorly then medially
   g. Anteriorly then medially
   h. Posteriorly then medially
16. Medialization should proceed no farther than:
   a. Ilioischial line (Kohler's line)
   b. Iliopectineal line
   c. Shenton's line
   d. Sourcil
17. In a standard primary hip, acetabular cup inclination is traditionally taught to be:
   a. 10-15 degrees
   b. 15-30 degrees
   c. 30-45 degrees
   d. 45-60 degrees
   e. 60-75 degrees
18. In a standard primary hip, acetabular cup version is traditionally taught to be:
   a. -35 to -15 degrees of retroversion
   b. -30 to -10 degrees of retroversion
   c. -25 to -5 degrees retroversion
   d. -20 to 0 degrees of retroversion
   e. -15 degrees retroversion to 5 degrees anteversion
   f. -10 degrees retroversion to 10 degrees anteversion
   g. -5 degrees retroversion to 15 degrees anteversion
   h. 0-20 degrees anteversion
   i. 5 to 25 degrees anteversion
   j. 10 to 30 degrees of anteversion
   k. 15 to 35 degrees of anteversion
19. During templating for a total hip arthroplasty, placing the femoral head center of rotation directly superior to the center of rotation of the acetabular component will have which of the following effects?
   a. Increase offset
   b. Decrease limb length
   c. Decrease offset
   d. Increase limb length
   e. No change in length or offset
20. Which of the following is a benefit of using large femoral head sizes during a total hip arthroplasty?
   a. Increased jump distance

b. Lower volumetric wear
c. Decreased cost
d. Lower rate of stripe wear
e. Improved range of motion

Appendix 2. ACGME Resident Milestones

Hip and Knee Osteo Arthritis (OA) – Medical Knowledge				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
• Demonstrates knowledge of pathophysiology related to hip and knee arthritis • Correlates anatomic knowledge to imaging findings on basic imaging studies • Demonstrates some knowledge of natural history of hip and knee arthritis • Demonstrates knowledge of hip and knee arthritis anatomy and basic surgical approaches • Demonstrates knowledge of non-operative treatment options and surgical indications	• Able to classify disease stage/severity and recognizes implications of disease processes (OA, Femoroacetabular impingement [FAI], inflammatory arthritis, osteonecrosis) • Understands the importance of comorbidities, thromboembolic prophylaxis, infection prevention and diagnosis • Correlates anatomic knowledge to imaging findings on advanced imaging studies • Understands the effects of intervention on natural history of hip and knee arthritis • Understands basic pre-surgical planning and templating • Understands basic implant choices (e.g., cement and uncemented fixation, levels of constraint)	• Demonstrates knowledge of current literature and alternative treatments • Understands biomechanics • Understands alternative surgical approaches (e.g., non-arthroplasty: arthroscopy, osteotomy) • Understands alternative implant choices/biomaterials (e.g., alternative bearings, unicompartmental approaches)	• Understands controversies within the field • Applies understanding of natural history to clinical decision-making • Understands principles of failure mechanism of total hip replacement (THR) and total knee replacement (TKR) (e.g., loosening, fracture, infection, osteolysis, instability) • Understands basic principles of revision THR and TKR	• Primary author/presenter of original work within the field • Understands revision THR and TKR implants (e.g., metaphyseal vs. diaphyseal fixation, tapered vs. fully-porous implants)
☐ ☐	☐ ☐	☐ ☐	☐ ☐	☐
Comments:				**Not yet rotated** ☐

Hip and Knee Osteo Arthritis (OA) – Patient Care				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
• Obtains history and performs basic physical exam • Appropriately orders basic imaging studies • Prescribes non-operative treatments (e.g., NSAIDs, physical therapy, assistive devices) • Provides basic peri-operative management (e.g., pre- and post-operative assessment) • Lists potential complications (e.g., infections, dislocations, thromboembolic disease, peri-prosthetic fracture, neurovascular compromise)	• Obtains focused history and performs focused exam • Appropriately interprets basic imaging studies • Manages non-operative treatment (e.g., NSAIDs, physical therapy, assistive devices, injections) • Completes pre-operative planning with instrumentation and implants (e.g., implant templating, instruments needed) • Capable of performing one basic surgical approach to the hip and knee • Provides post-operative management and rehabilitation (e.g., orders appropriate peri-operative medications and mobilization) • Capable of diagnosis and early management of complications (e.g., infections, dislocations) • Assesses for risk of thromboembolic disease	• Appropriately orders and interprets advanced imaging studies (e.g., MRI, CT, nuclear medicine imaging, and advanced radiographs views) • Appropriately recommends surgical intervention • Completes comprehensive pre-operative planning with alternatives • Modifies and adjusts post-operative treatment plan as needed • Capable of surgically treating simple complications (e.g., closed reduction, irrigation, and debridement) • Provides prophylaxis and manages thromboembolic disease	• Capable of performing alternative surgical approaches to the hip and knee arthritis • Capable of performing primary THR and TKR • Capable of treating complications both intra- and post-operatively (e.g., peri-prosthetic fractures, infections, instability)	• Competently performs two or more approaches to the hip and knee • Capable of performing complex primary and simple revision THR and TKR (e.g., hip dysplasia, hip protrusio, valgus knee, loose components, uniarthroplasty) • Develops unique, complex post-operative management plans (e.g., infections, dislocations, neurovascular compromise) • Surgically treats complex complications (e.g., peri-prosthetic fractures, knee instability)

☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Comments:

Not yet rotated ☐

Appendix 3. List of Critical Errors in THA.

1	**Lack of Progress**	No progress made in current surgical step for an entire minute. Dealing with the consequences of a predefined error represents lack of progress if no progress is made in the present step during this period.
2	**Incorrect Plane of Dissection**	The dissection is conducted outside the recognized plane of the posterolateral approach to the hip (i.e. dissection carried posterior or anterior to the femur).
3	**Unsafe Use of Saw**	Surgeon not able to demonstrate ability to control oscillating saw - threatens or causes damage to greater trochanter.
4	**Inability to Control Acetabular Reamer**	Surgeon not able to demonstrate ability to keep reamer in desired location. Reaming through medial wall of acetabulum.
5	**Damage Threatened to Neurovascular Structures**	Unaware of leg position needed to protect sciatic nerve during dissection, unsafe placement of retractors into sciatic notch, far anterior placement of anterior acetabular retractors
6	**Unsafe femoral preparation**	Unable to enter canal with broach/canal finder. Canal perforation, damage to greater trochanter, or femoral fracture.

Adapted from: Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Annals of surgery*. 2002;236(4):458.

Appendix 4. Cadaver THA Score Sheet.

Surgeon:______________________ Assist:________________________ Evaluator:_____________________

	1	2	3	4	5
Procedural Scores					
Palpates and marks surgical incision site					
Incision in line with femur dstally, curving posteriorly toward PSIS proximally					
Uses retractors for exposure in superficial dissection					
Identifies and exposes iliotibial band					
Incises IT band in line with femur - done separately from GMax split					
Bluntly splits Gmax and places Charnley retractor deep to it					
Exposes short extenal rotators					
Positions hip to protect sciatic nerve - hip extension, knee flexed					
Identifes piriformis and dissects proximally toward acetabular rim until labrum encountered					
Leg is internally rotated, putting short external rotators on stretch					
Short external rotators detached from femur without leaving residual tissue behind					
Dissection distally to Gmax tendon					
Does not endanger sciatic nerve					
Places tag sutures into piriforis and capsule/short external rotators					
Incises hip joint capsule					
Safely dislocates the hip					
Femoral neck cut perpendicular to neck					
Neck cut is in distal 1/3 of femoral neck					
Safely uses saw					
No injury to greater trochanter					
Removes femoral head					
Places retractors to expose acetabulum					
Excises labrum, pulvinar					
Begins acetabular preparation with smaller reamers and sequentially upsizes to appropriate diameter					
Reaming does not violate medial wall or ream out columns					

	1	2	3	4	5
Acetabular cup size selected appropriately based on final reamer					
Cup placed in approximately 15-25 deg anteversion and 30-50 deg inclination					
Cup is fully seated in prepared acetabulum					
Liner trial placed					
Lower extremity repositioned for femoral preparation					
Acetabular retractors removed, appropriate femoral retractors placed					
Abductors protected					
Box osteotome					
Canal finder					
Safe use of lateralizing reamer					
Sequentially upsizes reamers					
Uses small broach and upsizes sequentially					
Listens for auditory pitch change to indicate broach is seated					
Safe broach removal demonstrated					
Final broach appropriately sized and seated					
Trial femoral neck and head placed on to broach					
Hip reduced					
Stability testing - max flexion, flex to 90 with IR, combined anteversion, position of sleep, hip extenson with ER					
Checks leg lengths					
Overall Score					
Knowledge of specific procedural steps: Understands steps of procedure, potential risks, and means to avoid/overcome them					
Technical performance: Efficiently performs steps, avoids pitfalls, respects soft tissue					
Visuospatial skills: 3D spatial orientation, able to position instruments/hardware where intended					
Efficiency and flow: Obvious planned course of procedure with economy of movement and flow					

Ottawa Scale	1	Requires complete hands-on guidance, did not do, or was not given the opportunity to do
	2	Able to perform tasks but requires constant direction
	3	Demonstrates some independence but requires intermittent direction
	4	Independent, but unaware of risks and requires supervision for safe practice
	5	Complete independence, understands risks and performs safely, practice ready

Appendix 5. VR Pre-Quiz.

Record ID ______________________________

Background

First Name ______________________________

Last name ______________________________

Gender

- ◯ Male
- ◯ Female

Previous Experience

What year of training are you in?

- ◯ MS-1
- ◯ MS-2
- ◯ MS-3
- ◯ MS-4
- ◯ PGY-1
- ◯ PGY-2
- ◯ PGY-3
- ◯ PGY-4
- ◯ PGY-5
- ◯ Fellow

Have you ever played video games before (including smartphone games)?

- ◯ Yes
- ◯ No

What platform have you played video games on?

- ☐ Console (Xbox, Playstation, Wii, etc.)
- ☐ PC
- ☐ Smartphone and Tablet
- ☐ Virtual Reality (Oculus, Vive, Samsung VR)
- ☐ Other

If other, what platform(s)? (Write n/a if no other platforms)

____

What video game genres have you played?

- ☐ Action
- ☐ Adventure
- ☐ Casual
- ☐ Horror
- ☐ Indie
- ☐ Massive Multiplayer Online
- ☐ Puzzle
- ☐ Racing
- ☐ Role Playing Game
- ☐ Shooter
- ☐ Simulation
- ☐ Sport

Do you consider yourself a regular video game player?

- ◯ Yes
- ◯ No

When was the last time you played a video game?

- ○ Within the past 7 days
- ○ Within the past 4 weeks
- ○ Within the past 12 months
- ○ Greater than 12 months ago

During a typical week when you play(ed) video games, how many hours would you estimate were/are spent?

- ○ Less than an hour
- ○ 1-2 hours
- ○ 3-4 hours,
- ○ 4-8 hours
- ○ More than 8 hours

Have you ever used a virtual reality system before?

- ○ Yes
- ○ No
- ○ I own(ed) a virtual reality system

How much total time do you estimate you have spent using a virtual reality previously?

- ○ Less than 20 minutes
- ○ 20 minutes to 1 hour
- ○ 1 hour to 4 hours
- ○ More than 4 hours

VR Pre-Assessment

How interested are you in using this virtual reality surgical simulator?

- ○ No interest
- ○ Mildly interested
- ○ Somewhat interested
- ○ Very interested
- ○ Extremely interested

How realistic do you think this surgical simulator will be?

- ○ Completely unrealistic
- ○ Unrealistic
- ○ Somewhat realistic
- ○ Realistic
- ○ Completely realistic

How much do you think this virtual reality surgical simulation session will contribute to becoming a better surgeon.

- ○ Not at all helpful
- ○ Mildly helpful
- ○ Helpful
- ○ Very helpful
- ○ Extremely helpful

What percentage of a total hip arthroplasty procedure do you think you can perform?

0% 50% 100%

(Place a mark on the scale above)

What percentage of a total knee arthroplasty procedure do you think you can perform?

0% 50% 100%

(Place a mark on the scale above)

Appendix 6. VR Post-Quiz.

Record ID ______________________

Background

First Name ______________________

Last name ______________________

Gender

- ◯ Male
- ◯ Female

VR Post Assessment

Are you interested in continuing to use the surgical simulator to practice different arthroplasty procedures?

- ◯ No interest
- ◯ Mildly interested
- ◯ Interested
- ◯ Very interested
- ◯ Extremely interested

In your opinion, will the surgical simulator positively impact the training of orthopedic residents and fellows?

- ◯ Yes
- ◯ No

How immersive was this virtual reality surgical simulation program.

- ◯ Not at all
- ◯ Mildly immersive
- ◯ Somewhat immersive
- ◯ Very immersive
- ◯ Extremely immersive

How well do you believe this surgical simulator assessed your surgical/technical skill?

- ◯ Not at all
- ◯ Mildly accurate
- ◯ Somewhat accurate
- ◯ Very accurate
- ◯ Extremely accurate

What percentage of a total hip do you think you can perform surgery?

0% 50% 100%

(Place a mark on the scale above)

What percentage of a total knee do you think you can perform surgery?

0% 50% 100%

(Place a mark on the scale above)