SKILL ACQUISITION PROCESS OF A ROBOT-BASED AND A TRADITIONAL SPINE SURGERY

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Abstract: Technological progress greatly revolutionizes medicine. Robots give the opportunity to reach greater accuracy and thus improve the medical outcome. The results of a surgical intervention profoundly depend on the robot system and on the training state of the operator. Since the learning of a surgical intervention can be influenced by the complexity of the system, these interconnections are investigated with psychological methods. Therefore, the skill acquisition process of a robot-based surgery is compared to a traditional spine surgery. The usage of an appropriate robot shortens the learning curve of a spine surgery due to a decreased complexity and reduces the impact of the surgeons' psychomotor abilities on the surgery's outcome. For the design of a surgical system, different realizations must be tested in advance regarding their cognitive workload to avoid training costs learning the operation of the system, afterwards. The methods used are not restricted to surgical robotics.

1 INTRODUCTION

Medicine is one of the oldest sciences, as human beings have always had a thirst for knowledge about diseases and disorders. The development of technology revolutionized medicine: in 1625 the first microscope gave the opportunity to learn about both bacteriology and chemistry (http://techandmed.tripod.com/files/basicpages/history.htm), but only in the 21st century robotic systems were approved for surgery (http://electronics.howstuffworks.com/robotic-surgery1.htm). Their capability to deal with large amounts of data compensates for possible human errors. Robots work more accurately and reduce the convalescence time and possible traumata. Nevertheless, with the use of robots, the surgical process changes drastically and surgeons must acquire additional skills. The design of the machine, the man-machine interface, as well as the process of surgery are limiting factors for the learning complexity and are thus, responsible for clinical results. However, the skill acquisition process with a medical robot in particular is not well understood so far. Considering the learning process in an early stage of the system development may optimize the outcome of the system and reduce the costs drastically, which accumulate for the training of the stuff. This interdisciplinary study between engineering, medical, and psychological sciences is one step to provide methods for the evaluation of the interconnection between the learning process and the

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system design. Hopefully, it will help the designers developing their technical systems to fit human skills.

As an example of a technical system, the hand-held device Intelligent Tool Drive (ITD) for bone treatment (Pott, 2003) is investigated. In its first application, it will be used for stabilizing two or more vertebrae (arthrodesis) requiring the surgeon to drill holes into the pedicles of the vertebrae in question. Fig. 1 roughly explains a vertebra's anatomy.

Figure 1: Anatomy of a vertebra.
(a) refers to the pedicles, (b) to the vertebral body.

To drill holes manually into the pedicles is a difficult task as there is no room for mistakes: first, the drill is only about 1 to 2 mm smaller than the pedicles. Additionally, the surgeon cannot constantly check his or her work with X-rays or similar procedures due to the amount of radiation on both the surgical team and the patient. Thus, the surgeon needs experience to combine the feedback of the drill's resistance with the knowledge of anatomy to figure out whether he or she is drilling at the right place. Although this is a routine surgery about 30% of the screws are not set ideally, about 5-6% of these require repeated surgery (Siebert, 2000).

The concept of the ITD allows the improvement of this type of surgery, especially regarding the drilling process's accuracy. The desired drilling position is planned before the intervention basing on 3D computer tomography. During the intervention, the robot system measures the actual position of tool and patient and controls the accurate positioning of the drilling tool. In this way disturbances and displacements by the surgeon, which holds the robot in his or her hands, can be compensated.

Implementing the ITD will require the surgeons to perform the surgery a completely different way. With the ITD the surgeon must plan the drilling trajectories and he or she must find anatomic positions for the matching of the robot coordinates with the patient coordinates. Little research has been done on the process to acquire the skill to perform surgery, although it is completely different applying new tools, so that it is obvious that the new method must be learnt. Is the skill acquisition process shorter or qualitatively different when using a device compared to a traditional surgery? What if the new tool requires all of the surgeon's attention and no resources are left for the patient? Which are the underlying abilities determining the learning process? Can the impact of these abilities be changed through implementing the ITD in a especially easy way, so that the need for skill acquisition is reduced? An interdisciplinary approach has been taken to start answering some of these questions, and to give a first set of directions so that the possibilities the robot offers can be full taken advantage of. The following solution approach gives necessary input to theoretically answer these questions; the performed experiment gives the first set of answers.

2 PROBLEM STATEMENT AND SOLUTIONS APPROACH

2.1 Skill Acquisition Theory (Ackerman, 1988)

Ackerman distinguishes between three phases within the skill acquisition process, each of which is determined by other abilities (Fig. 2). The first phase, which is referred to as the cognitive phase, is characterized through slow performance and few errors. While practicing the learners need to build productions, which are "if...then...clauses" that connect a condition specifying when the actions must be applied and the action itself (Anderson, 1980). If for example the traffic light turns red, then the car driver must break. The process of building productions requires both cognitive and attentional resources (Ackerman, 1988).

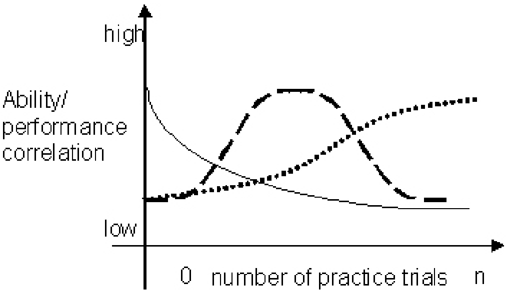

Figure 2: Demonstrates the three phases of the skill acquisition process. The first phase is given via the straight line, the second one via the dashed and the third one via the dotted line (adapted from Ackerman, 1988).

After having acquired a broad cognitive representation of the task, the learner proceeds to the associative phase. Practicing now results in finding easier ways to reach the same result, in generalizing the productions to other similar tasks, in eliminating sub-goals and in strengthening the productions. The ability, which determines this phase's performance, is the ability to compare the stored information with the information about the new situation and to act based on the outcome of this comparison. These are defined as psychosensoric abilities (Ackerman, 1988).

In the last phase, which is called autonomous processing, learners thoroughly understand the task and have developed efficient productions that can be performed automatically without or with only few attentional/cognitive demands. Performing the task is thus fast and accurate and the performance is only limited by psychomotor abilities (Ackerman, 1988).

2.2 Factors influencing the prototypical skill acquisition process

This description of a skill acquisition process is only prototypical. As already mentioned cognitive abilities for example influence the way to learn, so that interindividual differences result in qualitatively different skill acquisition processes. However, not only characteristics of the learner but also the ones of the task influence the way to learn.

2.2.1 Characteristics of the task

A more complex task is – generally speaking – a more difficult one, which results in a prolonged cognitive and associative phase, so that the overall skill acquisition process takes longer. Regarding the robot-based spine surgery this has two major consequences: first, the learning process is shortened if its productions are less complex and second the learning process can further be simplified if the tool's application is made less complex. A comparison between the traditional way to perform surgery and the robot-based one reveals that some components are added to the traditional way, which make it more difficult. The surgeon for example has to "explain" the ITD on a 3D model of the patient, where the hole should be ideally placed. However, very difficult components are no longer needed. When operating with the ITD the surgeon no longer needs to consider the drill's resistance in order to figure out whether he or she is drilling at the right spot or not. This is a great relief for the surgeon. An exact and enclosing comparison of both methods is out of the scope of this article, however it reveals that the robot-based surgery is altogether less complex, so that it can be inferred that the skill acquisition process is shortened.

Task consistency refers to the number of invariant rules for completing the task in question successfully (Ackerman, 1987). If the task is inconsistent, no general valid productions can be generated, so that the task cannot be acquired. As the ITD is used in a critical medical context, the rules for deciding when a given production is to be used must be highly consistent, so that learning takes place.

2.2.2 Characteristics of the learner

Interindividual differences do determine performance during the skill acquisition process: cognitive abilities influencing the first, psychosensoric the second and psychomotor abilities the third phase of the skill acquisition process. The first two refer to intelligence. The model of intelligence on which the study is based on is the Berlin Intelligence Structure Model developed by Jäger (1982). This hierarchical model distinguishes between two facets: operations and contents. The contents refer to the type of material that must be processed; the operations define what must be done with the content. The figural content determines performance during surgery. It for example requires the surgeons to interpret the information on two-dimensional X-rays three-dimensionally. An operation is for example reasoning, which refers to the ability to solve problems. Perceptual speed, another operation, is related to the speed of the work on simple, cognitive tasks. As this description shows, the latter operation is closely related to the cognitive requirements in the second phase, reasoning to the requirements in the first phase.

How does the skill acquisition process change when comparing two learners, one with high reasoning, figural abilities, and perceptual speed, and the other one with low abilities? Learners who are more able show greater performance levels and thus proceed to the next phase faster, because they build productions that are more exact faster. As in the next phase, this ability no longer predicts performance and interindividual performance differences are then balanced, if the learners have the same level of the ability influencing performance in the next phase. However, the advantage, the more able learners have already gained, will not be caught up by the others, so that learners with higher ability levels have a general shorter and steeper learning curve.

The individual differences in both the performance level and the time needed to reach the level where the next phase starts can be reduced if the abilities underlying the first and second phase can be made less important. As already described, an increased task complexity makes both the cognitive abilities and the psychosensoric ones more important, so that their influence can be reduced through reducing task complexity. Therefore, the robot-based and the traditional spine surgery have already been compared with the result that the robot-based one has been rated as less complex. Thus, the first major accomplishment of implementing the robot is a shortened skill acquisition process.

Another major factor heavily influencing the skill acquisition are psychomotor abilities. Psychomotor ability reflects the ability to react fast on tasks that require little or no cognitive processing at all (Ackerman, 1988). The abilities influencing the success of the surgery in question are limited to arm and finger movements: precision and co-ordination. A participant with low abilities shows a slower course of the acquisition process but also fails to reach the same performance level. This difference has huge consequences for the success of a surgery: a surgeon with higher psychomotor abilities will manage the challenges of the surgery a lot better than one with less psychomotor abilities even after having acquired the skill. This is especially important, as here the drill's resistance must be analyzed and the operator must react with very fine motor movements. Psychomotor abilities thus decide on success or failure in a traditional surgery. Here, the second accomplishment of implementing the robot is apparent: the robot reduces the impact of different ability levels and thus enables not only surgeons with very high psychomotor abilities to perform this type of surgery.

2.3 Problem Statement

Summarizing, the ITD's implementation theoretically has two major accomplishments: it reduces the impact of psychomotor abilities, so that at the end of the learning process learners with less abilities do not show a lower level of performance. Second it reduces the impact of the cognitive abilities because of its decreased complexity, so that the learning process is shorter. However, the positive effects can be reduced if the robot-based surgery is made more complex than it needs to be and thus increases the cognitive workload. Therefore, a thorough analysis is necessary even before the completion of the tool to make the robot benefit from synergies between engineering and psychology.

The registration of a vertebra, i.e. the matching of the robot and the patient coordinate frames, is a good example to demonstrate a possible reduction of the ITD' advantages. There are a couple of algorithms which could work, however these vary regarding the challenges for the surgeon. One algorithm with which the matching could be performed is the surface matching. Here, the surgeon needs to scan the vertebrae using a pointer. The scanned area should be as big as possible to ensure successful matching. The computer tries to align these scanned points on the patient's bones with the 3D model to identify the vertebra that must be performed surgery on. In contrast to the surface matching, pair-point matching determines exactly which points of the vertebrae must be scanned. The surgeon then has to exactly identify the relevant points on the screen, he or she has to find these points on the patient and scan them. The probability of successfully matching the 3D model and the actual vertebra is here augmented, whereas the scanning process is more complicated. Theoretically, the surface matching should be chosen for the ITD's implementation. Otherwise the more complex production needed to acquire the pair-point matching which would make the robot-based surgery more complex and thus reduce its positive effect compared to the traditional surgery.

The experiment was designed in order to test the impact of the matching procedure on the work load of the surgeon, but it is also used to start research in this field, showing that a learning curve is apparent to validate Ackerman's theory and implement it as a basis for future research. These are the research questions to be addressed:

-Does learning take place when operating the spine?

-Is the learning curve concordant with Ackerman's skill acquisition theory? The theory is tested empirically via the factors reasoning, figural abilities, general intelligence, which should have high predictive validity coefficients for the first practice trials. The second and third phases was not tested.

-Do the learning curves differ regarding the cognitive workload? Altogether two learning curves result out of this experiment: one without matching, and one with the pair-point matching. This hypothesis tests the impact of the performance of the matching procedure on the skill acquisition process regarding the cognitive phase. Through adding one component of the robot-based surgery to the traditional one, the answer of this hypothesis is an important step to make the ITD cognitively as easy as possible for the surgeon and thus to make major advantage of the ITD's implementation.

3 EXPERIMENT

3.1 Participants

The experiment's participating group was one of convenience: the participants were recruited in lectures at the University of Mannheim, so that all participants were students (50% male, 50% female). Surgeons could not be recruited due to their strict time schedule. Also, not enough students of medicine could be convinced to participate, so that 17 participants study a major related to computer science, 17 psychology, 5 medicine and 5 were from other majors such as business. The group size of 44 was set so that possible medium effects can be detected according to the standards set by Cohen (1992). The reported average drilling experience was little, whereas test theoretical problems might have biased the results.

3.2 Apparatus and instruments used

Reasoning, general intelligence and figural abilities were measured to predict performance regarding drilling time and accuracy in the cognitive phase of the skill acquisition process.

The diagnostic tool used to collect information on intelligence was the Berlin Intelligence Structure Test (BIS-4) (Jäger, Süß & Beauducel, 1997). The short version of the test was used to assess general intelligence and reasoning. For collecting data on figural abilities, some further tasks were added to the test. These resulting 25 tasks were separated into two booklets, in between which a break of 10 minutes was included. Both the standardization of the administration and of the analysis given in the test's manual were used to ensure objectivity. Other major criteria of the test were repeatedly measured for the BIS-4 and showed good results (for a summary see (Jäger, Süß & Beauducel, 1997)). It was decided to work with this test first because the BIS-4 measures all relevant information needed to investigate the cognitive phase, and second because the test's quality criteria are highly promising.

The time needed to drill was measured with a standard, digital stopwatch during the drilling processes. The stopwatch was started when the drill first touched the vertebra and was stopped as soon as the participant told the experimenter that he or she is finished. The recorded time was reported to the participants as feedback, which is necessary to enhance the skill acquisition process. Regarding accuracy, the participants were told to drill exactly 20 mm deep, directly in the vertebra' center, at an angle of 90^o and were told to watch that the surface area of the drilling to make sure it was not getting too big. The depth, the surface area, and the deviation from the center were all based on measures of an electronic digital caliper (repeatability accuracy: 0.01 mm). The angle was assessed with a stick of wood that had the same diameter as the drill (4mm), which was put into the drilled hole and was adjusted to a vertical line. With an angle made of steel the biggest deviation from the ideal angle of 90^o was recorded. If the participants performed the matching, another variable was included into the accuracy index: the success of the matching trials. Feedback on each point was given after each trial to the participant.

3.3 Experimental set-up

The experiment took place in two sessions. In the first one, which was between 1.5 and 2 hours long, participants performed the selected tasks of the BIS-4. They were tested in groups with a maximum size of 9 participants. The second session took place between 1 and 2 weeks later with one participant each and also took about 1.5 and 2 hours depending on the condition into which the participants were grouped randomly: the matching versus no matching group. The second session started with a short explanation of the experiment. While reading the instructions to the participants, the procedure was explained on a sketch of the "spine" used in this experiment. These sketches roughly showed the experimental setting: a piece of wood lying on the table represented the spine, into which six round sticks were inserted roundly shaped at the top. These six pedicles were hidden under a towel during the whole experiment, so that the participants had no visual information about their shape, and were used in order to perform the matching. The participants had to find the highest point of a pedicle of their choice and had to touch it with a pointer and then press a switch lying on the floor. This pointer was adapted in shape and size to the one used in the medical setting. The pointer and the pedicles were electrically connected to a display box. As soon as the participant pressed the switch, two lights indicated to the experimenter that first the switch had been pressed, and second whether the highest point had been touched or not. The participants could choose the pedicle they wanted to match with one constraint: it was not allowed to use the same one twice in a row.

After having performed two of these matching trials, one drilling procedure was performed. The drilling process was the same in both groups: The hole had to be drilled into similar vertebrae, that were arranged on the other end of the "spine": from

16 vertebrae 10 had to be chosen. Each vertebra was about 30 mm long and 12 mm wide and was inserted into a bush made of aluminum that was inserted into the "spine". The drilling itself was made with a portable drilling machine. Except the pointer and the drilling machine, no other tools were used. The pedicles into which the hole had to be drilled were not hidden and were straight at the top. Last, a final questionnaire was answered in order to collect demographic data on the participants. The spine on which both the drilling and the matching have been performed is given in Fig. 3.

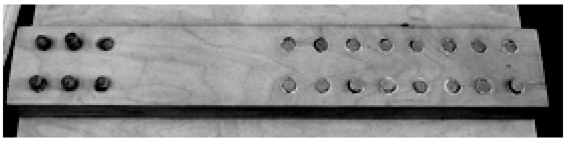

Figure 3: The "spine" used in this experiment. On the left side the vertebrae used for the matching procedure are displayed, the ones on the right side were used for the drilling procedure.

3.4 Results

3.4.1 Pre-Analysis

Each variable indicating accuracy was tested with the F-distribution to figure out whether a learning effect took place. These are the results:

-For the deviation from the ideal depth the learning factor is significant with a probability of $p = 0.000$ $(F(9,387) = 16.687)$. A learning effect with an effect size of $f^2 = 0.388$ was found indicating how many standard deviations the participants improved their drilling.

-For the deviation from the ideal angle the learning factor, is significant with an error probability of $p = 0.031$ $(F(9,387) = 2.069)$. The effect size was calculated as $f^2 = 0.049$.

-For the deviation from the center, no learning effect took place, which might be based on the inaccurate feedback given to the participants. The probability is $p = 0.171$ $(F(9,387) = 1.436)$, which is bigger than the accepted critical value of $p = 0.05$ to mistakenly reject the hypothesis, that no effect is there, although one exists. The size of the learning effect was calculated as $f^2 = 0.033$, which shows that an effect might be there, however, not big enough to be detectable with the number of participants tested.

-For the surface area the learning factor is significant with a probability of $p = 0.016$ $(F(9,387) = 2.303)$. The effect size was calculated as $f^2 = 0.053$.

-For the matching procedures the learning factor is significant with a probability of $p = 0.000$ $(F = 9,189) = 4.548$. The effect size was calculated as $f^2 = 0.216$.

As the learning curve is analyzed, the accuracy index is only made up of those variables showing a learning effect. These variables were transformed to delete the information about the measurement unit and about the ideal value, so that each single variable gives information about the number of units the ideal value has not been met. The mean was calculated out of these transformations to indicate the overall accuracy. The data set was also checked for extreme values and two participants had to be excluded.

The drilling time measures showed many extreme values. As this might result in non-significant results when testing the hypotheses, the time measures were transformed logarithmically. Despite this transformation, one participant had to be excluded from the analysis.

3.4.2 Significance testing

Finally, the research questions can be answered:

-Does learning take place when operating the spine regarding drilling time? The analysis shows a significant learning factor $(F(9,360) = 10.661$, $p = 0.000)$ with an effect size of $f^2 = 0.266$. Curvilinearity is tested as well with significant results: the linear trend is significant with $p = 0.000$ $(F(1,40 = 29.165$, $f^2 = 0.729)$, the quadratic one with $p = 0.000$ $(F(1,40) = 7.825$, $f^2 = 0.679)$ and the cubic effect with $p = 0.001$ $(F(1,40) = 12.343$, $f^2 = 0.308)$ giving information about the learning curve's shape.

-Does learning take place when operating the spine regarding accuracy? The learning factor is significant as well with $p = 0.000$ $(F(9,351) = 0.725$, $f^2 = 0.566)$. The linear trend is also significant with $p = 0.000$ $(F(1,39) = 67.372$, $f^2 = 1.713)$, the quadratic one with $p = 0.000$ $(F(1,39) = 17.042$, $f^2 = 0.449)$ and the cubic one with $p = 0.032$ $(F(1,39) = 4.917$, $f^2 = 0.116)$. Fig. 4 shows the learning curve of all participants over all trials.

-Is the learning curve concordant with Ackerman's skill acquisition theory regarding drilling time? Testing this interaction effect between learning and the cognitive factors reveals the following results: The interaction effect between the learning factor and reasoning is significant with $p = 0.010$ $(F(9,333) = 2.446$, $f^2 = 0.066)$, the interaction effect between the learning factor and general intelligence is not significant with $p = 0.669$ $(F(9,333) = 0.744$, $f^2 = 0.020)$ and the interaction

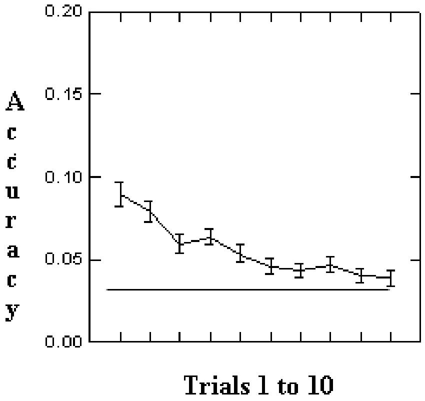

Figure 4: Line plot of the accuracy levels over all trials. Smaller numbers indicate better accuracy. The asymptote shows that the participants do not reach a perfect accuracy level.

effect between the learning factor and general intelligence is not significant with p = 0.913 (F(9,333) = 0.440, $f^2 = 0.012$). Reasoning shows a significant quadratic trend with p = 0.016 (F(1,37) = 6.389, $f^2 = 0.172$).

-Is the learning curve concordant with Ackerman's skill acquisition theory regarding accuracy? The interaction effect between general intelligence and the learning factor is significant with p = 0.010 (F(9,324) = 2.463, $f^2 = 0.069$), the interaction effect between the figural abilities and the learning factor is significant with p = 0.002 (F(9,324) = 3.003, $f^2 = 0.084$) and the interaction effect between reasoning and the learning factor is not significant with p = 0.113 (F(9,324) = 1.539, $f^2 = 0.042$). The curvilinear trends also reveals significant results: the linear trend is significant for the interaction between general intelligence and the learning factor with p = 0.040 (F(1,36) = 4.539, $f^2 = 0.131$) as well as the linear trend for the interaction between figural abilities and the learning factor with p = 0.007 (F(1,36) = 8.238, $f^2 = 0.229$). The cubic trend is also significant but only regarding the interaction between the learning factor and general intelligence with p = 0.010 (F(1,36) = 7.361, $f^2 = 0.200$). Fig. 5 visualizes the different learning curves for the more and less intelligent participants.

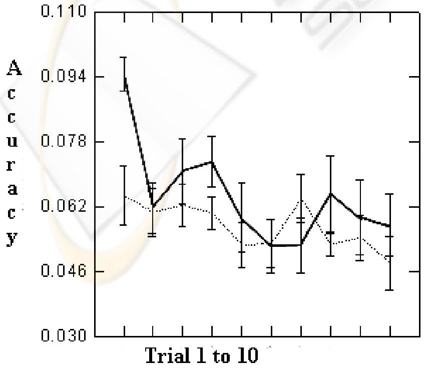

Figure 5: Line plot of the two learning curves for the less able participants (straight line) and the more able ones (dotted line). Smaller numbers indicate better accuracy.

-Do the accuracy's learning curves differ regarding the cognitive workload? A three-way interaction effect between the cognitive factors, the variable that groups the participants into their experimental condition and the learning factor must be tested: the result is not significant for general intelligence with p = 0.921 (F(9,324) = 0.427, $f^2 = 0.010$), for reasoning with p = 0.766 (F(9,324) = 0.636, $f^2 = 0.017$) and for figural abilities with p = 0.988 (F(9,324) = 0.245, $f^2 = 0.007$).

For all tests, the assumptions underlying the statistical significance tests were checked, and none of them was severely violated. Further, the stability of the results was tested revealing very little variation regarding the reported effect sizes, so that the results can be interpreted.

3.5 Discussion, conclusion, and final remarks

First of all, this study shows that it is both necessary and possible to learn to perform surgery. Drilling time shows a large learning effect: the participants got faster with the number of trials performed until about the 7th trial. It is surprising that learning interacts with the participants' reasoning abilities in the following way: the more able participants need more time to drill, show a longer learning process and also improve their timing less than do the less able participants. It is in this respect concordant to the theory that reasoning actually predicts the acquisition process, however, the effect's direction must be discussed. Probably the more able participants focus on accuracy, so that the drilling time is a less important factor for them. The participants with greater figural abilities drill more accurately, need less time to reach a comparable accuracy index, and acquire the skill faster. The same is true for general intelligence. As the latter is based on various components of less general intelligence factors such as reasoning or figural abilities, this is not surprising. Especially general intelligence shows relatively high correlations with reasoning, however, without causing statistical problems. This might be a reason for the results regarding intelligence and drilling time. Altogether, the results confirm Ackerman's theory: skill acquisition takes place for both time and accuracy and the learning process depends in its first phase on intelligence. The learning curve for accuracy is altogether longer than the one for the drilling time.

Here about 9 to 10 trials are needed to reach the phase in which the cognitive factors no longer play an important role. Fig. 4 further demonstrated that human beings do not reach a perfect accuracy level, and gave a benchmark on the accuracy level of the human beings that the robot must exceed. As this "spine surgery" has only been a rough sketch of the real surgery, one can be imagine how much bigger the already detected medium-sized effects could be if tested in the real word. Last, the impact of the pair-point matching procedure on the skill acquisition's cognitive phase is not significant, so that a possible effect has either been too small to be detectable with the number of participants tested or the effect might not be there. The results indicate that the implementation of the pair-point matching procedure, thus, does not impede the robot's positive impact.

Our simulation demonstrated that the input from psychology paid off. This article provides methods to analyze the demands on any technical system in respect to the human skill acquisition process as an important system design factor. Skill acquisition theory worked in predicting and explaining performance. Therefore, let us look at the demands to be put on an excellent robot through the lens of skill acquisition theory:

a) A robot should at least in the long run reduce the cognitive load on the surgeon. The surgeon then can invest his or her cognitive resources on other parts of the surgery.

b) A robot should reduce the time it takes to acquire a skill. In the long run, this should contribute to reduce the inevitable costs of introducing it.

c) Reducing cognitive load the robot should enable a larger percentage of medical doctors to learn and do high-quality surgery.

d) A robot should reach a level of accuracy sooner and outperform the benchmarks set by traditional methods in terms of much higher accuracy.

Will our ITD fulfill these promises? Well, we are working hard on it and future research will tell you how much we succeeded.

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