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Method Article

The Economy of Motion for Laparoscopic Ball Clamping Surgery: A Feedback Educational Tool

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ABSTRACT

The Ball Clamping module of the Laparoscopic Surgery Training Box involves the transfer of beads across the training board using laparoscopic tools. Fundamentals of Laparoscopic Surgery (FLS) requires practitioners to move their hands at as short a distance as possible to perform the functions in the shortest amount of time. This study introduces a feedback tool that presents to the student, after attempting their exam, the right direction (step by step) of obtaining the optimal pathway for minimizing distance traveled in the Ball Clamping Module of the Laparoscopic Surgery Training Box. The shortest distance tour for the ball clamping task is determined using the Traveling Salesman Model (TSM). A sensitivity analysis is conducted to assess the model's applicability to different types and settings of trainer boxes.

- Find the best sequence of points resulting in the shortest distance tour for the ball clamping task.
- The effects of adding or removing columns from the box cannot be intuitively predicted.

Specifications table

Subject area:	Medicine and Dentistry
More specific subject area:	Laparoscopic Surgery Training Box
Name of your method:	Traveling Salesman Model (TSM), Sensitivity analysis
Name and reference of the original method:	J. Falcone, X. Chen and G. Hamad, "The traveling salesman problem in surgery: economy of motion for the FLS Peg Transfer task," *Surg Endoscopy,* vol. 27, pp. 1636–1641, 2013.
Resource availability:	The data are available in this article

Method details

Introduction

Laparoscopy is a surgical treatment procedure used to examine the organs inside the abdomen [1]. It is a low-risk, minimally invasive procedure requiring small incisions [2]. Laparoscopic surgery takes its name from a Laparoscope, a slender tool with a micro video camera and light at the end. In this surgery, the surgeon inserts the camera through the small incisions to observe the abdomen's interior via a video monitor.

The American Board of Surgery requires the residents to take and complete the Fundamentals of Laparoscopic Surgery (FLS) to be eligible for certification. The FLS includes many tasks that trainees must achieve within a specific time, such as the Peg transfer task.

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The Peg transfer task transfers six objects with a laparoscopic grasp tool in midair from the non-dominant hand to the dominant one. Then place each item on a peg on one side of the board and repeat the same process in reverse, starting from the dominant hand to the non-dominant hand. Finally, placing the objects back on the opposite side of the board with no particular order is required for the task [3].

Because of the small incisions and the need to use both dominant and non-dominant hands simultaneously, handling tools in Laparoscopy can be tricky and may require training beforehand. The training is based on the FLS program developed by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) [4]. The FLS program was launched in 2004 to assess the required surgical skills and the fundamental knowledge needed for laparoscopic surgery. Participants' skills are evaluated by completing simulation tasks, including peg transfer, pattern cutting, and placement of the ligating loop, followed by suturing and knot-tying training. Authors [5] developed predictive learning curve models for basic laparoscopic tasks to identify performers versus underperformers during selection into surgical training. Authors [6] used linear regression tests to predict the learning curve and the number of repetitions required to reach proficiency in laparoscopic skills.

These training boxes aim to imitate and create operating conditions that surgeons may encounter during surgery. It has a far-reaching improvement effect for the practitioner on the hand-eye coordination ability, hand-muscle control ability, and training of the non-dominant hand, which are the most critical fundamentals needed for Laparoscopy. The importance of physicians' training level is indicated as a crucial risk factor for unplanned emergency readmissions [7].

However, other training boxes often include different tasks with different patterns and designs. These boxes aim to train and assist surgical residents, students, and operating room assistants, allowing them to exercise the needed laparoscopy skills and complete the training in medical schools, universities, hospitals, and skills centers at a low cost. Training boxes shift the learning curve away from the patient, learn from errors and reduce operational procedure and instruction time at affordable prices [8]. Improving the efficiency of laparoscopic surgery has been investigated from various points of view. For example, simulation-based training in laparoscopic surgeries has been the best training practice [9]. The attitude and perceptions of trainees towards the value of basic medical sciences were investigated [10]. In the training practice, the trainees must perform and complete the Laparoscopic task within a certain amount of time; the shorter the time, the better. Therefore, the quality of the trainees' performance should be evaluated and fed back to them, informing them of the right detailed pathway that should have been taken after finishing their tests. Thus, TSM is utilized as a feedback tool to mimic the investigated problem and find the shortest distance.

Studies on the TSP applications in healthcare have attracted many researchers, including but not limited to [11], who investigated the shortest two-dimensional path length to complete peg object transfer tasks by dominant and non-dominant hands using the Traveling Salesman approach. Authors in [12] studied the problem of time spent changing tools in a modular surgical tool system. TSP was applied to identify the optimal queuing of tools based on patterns using sequences to allow surgeons to use the tools system more efficiently with less time, decrease the overall cost, and deliver the treatment with more quality. Another problem was investigated by [13], which is the morning rounds on patients. TSP was implemented to find the minimum distance a physician will travel to visit all his patients before returning to his office.

Authors in [14] used multiple TSP with Time windows (mTSPWT), including specific constraints such as skills to deal with the routing problem of health care staff in a home health care problem. Authors in [15] referred to the home healthcare scheduling and routing problem as a Vehicle Routing Problem with Time Windows (VRPTW) to assign tasks to nurses/caretakers and schedule their plans. Another application of the TSP in healthcare is the work done by [16] to find the optimal vehicle fleet necessary for medical product distribution.

From the above studies, TSP has been used in many healthcare problems, including peg object transfer, healthcare staff routing, distribution of medical products, etc. However, to our best knowledge, TSP has not been utilized yet in clinical applications like the problem on hand. This problem includes modeling the Ball-Clamping module and providing feedback to its trainees to assess the quality of their exam performance. The

This paper aims to elevate the surgical residents' training experience by providing detailed educational feedback after completing the students' Laparoscopic exam. The contribution is evident in implementing the traditional TSP for modeling the ball's movement from one column to another and returning to the origin in the Ball clamping module, achieving the shortest traveling time. It is worth mentioning that the novelty of this work is not restricted to TSP and its classical mathematical modeling formulation rather than utilizing them in a specific and critical surgical healthcare problem.

As a practical implication of this work, the Laparoscopic training assessors are the main beneficiary of using this application as they will provide constructive feedback to students after completing their tasks. This feedback ranks the various paths in terms of their distance traveled and shows them the most economical path should be taken. It enables a more objective and consistent comparison of trainee performance along similar paths after the trainees finish tours.

The laparoscopy ball clamping module

The ball clamping module can be used for different tasks in many ways. Our study focuses on using it in the Laparoscopic Surgery training module, in which it takes one ball from the holder and transfers it through all columns. The ball should rest on the top of each column and return to the starting point. There is no requirement regarding the order in which the trainee selects the columns. This problem involves visiting all columns (nodes) starting from the origin and returning to the exact origin. This behavior is similar to the well-known TSP in which a traveler leaves the source node completing the tour by visiting each node once and returning to the source node. Thus, the TSP model was selected to model this problem.

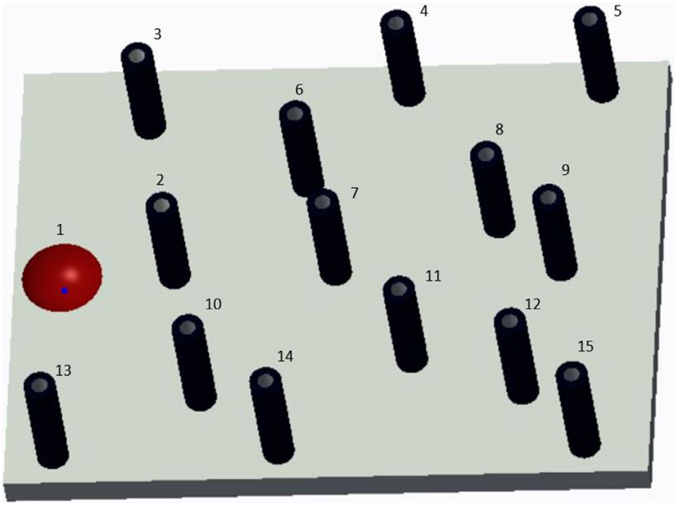


Fig. 1. Creo drawing of the ball clamping module.

Table 1
Distance matrix (symmetric: Distance from i to j = Distance from j to i).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0														
2	7	0													
3	12.08	11.18	0												
4	24.7	19.1	16.12	0											
5	35.47	29.07	28.07	12	0										
6	16.35	10.31	10.97	8.85	19.14	0									
7	17	10	16.28	13.6	20.62	6.8	0								
8	27.19	20.26	23.33	11.45	11.45	12.43	10.51	0							
9	31	24	28.23	16.4	13.15	17.27	14	5.15	0						
10	12.73	9.22	20.4	25.1	32.56	16.62	12.04	21.77	23.77	0					
11	22.94	16.35	24.4	19.5	22.39	14.76	8.2	10.95	11.1	13.24	0				
12	30.36	23.77	31.24	23.41	22.36	20.89	15	12.41	9.22	20	7.43	0			
13	13	14.76	24.52	33.42	42.01	24.6	21.4	31.51	33.62	9.85	22.94	29.27	0		
14	19.1	14.76	25.63	26.93	32.2	19.53	13.34	20.81	21.4	6.4	10.31	15.52	14	0	
15	35.47	29.07	36.88	28.64	26	26.54	20.62	17.32	13.15	18.44	12.78	5.66	33	19	0

The aim is for the laparoscopic surgery trainees to perform ball movement tasks quickly; this can be done by minimizing the total distance of their hands' movement. The goal is calculating the ball movement's minimum tour distance by applying the traveling salesman problem. This will result in the sequence of the points the ball should travel to before returning to the starting point. We are seeking an order or permutation that minimizes the total distance. Fig. 1 shows a schematic view of a Laparoscopy Ball Clamping module comprising 15 points across the board, created using Creo software.

Fig. 1 shows a 3D schematic view of the Ball Clamping Module with 15 points (14 columns and the source node). There are 1307,674,368,000 ways (15!) to complete the task with different sequences each time. The Laparoscopic Surgery trainee's task is to move the ball from one column to another and return to the origin on the Ball Clamping module in the shortest time. This task is actually to enhance the laparoscopic surgery skills of the trainee. Which of the massive number of tours is the optimum (in terms of minimum distance)? Identifying the optimal tour provides the best possible performance and can be used in the examination process of participants' skills.

In Fig. 2, a top-view cross-section of the Ball Clamping module shows the distances among the points. This module is symmetric since distances between every node are equal in both directions. The solution calculates the shortest distance tour considering this module a Symmetric Traveling Salesman Problem (STSP). According to [17], the network must be a complete undirected graph satisfying triangle inequality. In both directions, every two nodes are connected and linked with the same weight (distance in our case).

As Fig. 2 shows, the triangle inequality holds in geometric and weighted graph problems; any Euclidean geometry will satisfy the triangle inequality [18].

The distances matrix, which shows distances between all pairs of nodes of the considered training box, is shown in Table 1.

Plenty of training modules designed for Laparoscopy surgery are intended for residents, doctors, and students to increase their skills. Each has a different setup and design; hence, the distances matrix provided in Table 1 above is one of many options found in the market. An additional form will result in a different optimal path based on locations and distances. The suggested solution in this

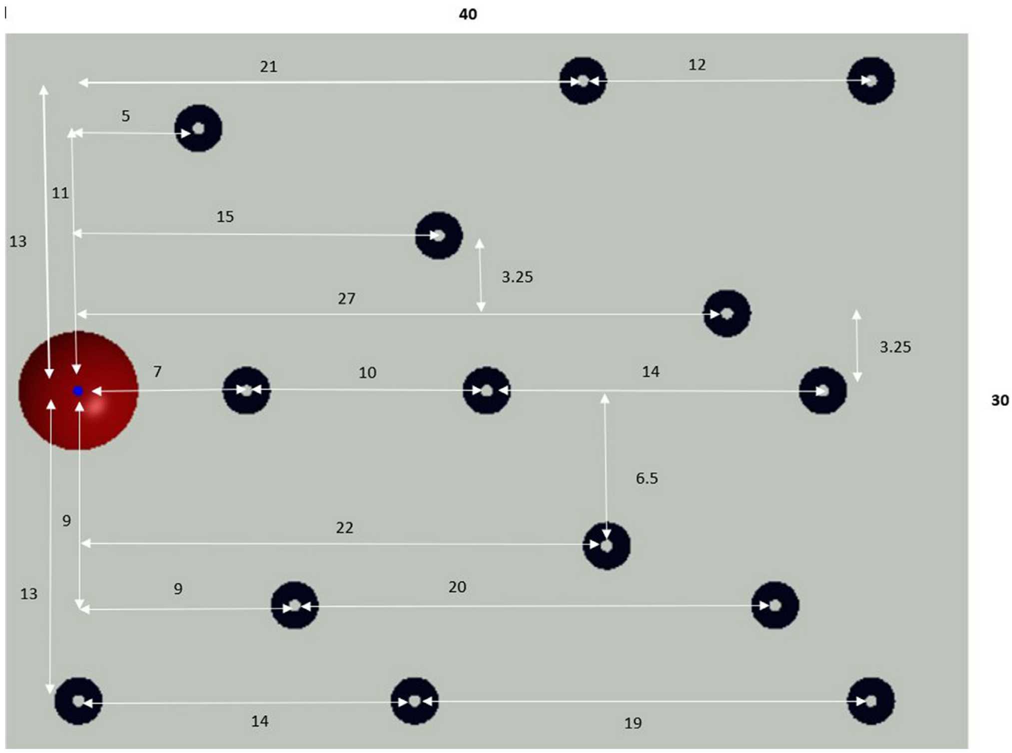


Fig. 2. Distances (cm) between Nodes (Top view).

study will help provide a quick reference for trainees without any further complications. The optimal distance tour/path between all nodes (columns) could then be presented to the trainees after finishing their training/assessment by a small screen fixed on the module box for their performance benchmarking purpose.

This solution could be adapted to any module design or different tasks or configurations in the same module by sending data, including nodes (pegs) and their distances, to the mathematical model for processing and returning with the optimized tour presented on the screen for benchmarking and performance evaluation purposes.

Utilization of TSP in laparoscopy ball clamping mathematical formulation

This section aims to utilize the TSP and its related mathematical formulation in modeling the Ball Clamping used in Laparoscopy Surgery training. The Ball Clamping module is a single routing problem on a complete undirected network $G = (V, E)$ satisfying the triangle-inequality, where V is the set of all columns on the module (number of columns $n = 15$), including the source/depot {1, 2, 3, …, 15}. E is the set of all virtual edges connecting all columns {(1,2), (1,3), (1,4), …, (1,15), (2,3), …, (14,15)}.

This model assumes the Triangle inequality holds. The $\Delta - ineq$ means that $\forall\ i,\ j,\ k\ \in V$, the following relationship holds: $d_{ik} \le d_{ij} + d_{jk} \quad \forall (i,j) \in E,\ \forall k \in V,\ \ k \ne i,j$

A TSP tour T on G is a sequence of all columns in V, $T = \{i_1,\ i_2,\ \dots,\ i_n,\ i_1\}$, where $i_k \in V$ and each i_k Unique $\forall k = 1, \dots, n$. Over one trillion tours start at column one and visit all other columns once before returning to the point the surgeon trainee started from (point 1 in Fig. 1). Another assumption in this study is that the distances are considered one-dimensional, excluding the practitioner's need to clamp the ball in the first movement to pick it up from the reference point and then move it across. Such an assumption is that the heights of the columns the ball will rest upon and then travel to are all the same, so calculating the vertical distances will not be beneficial.

The aim is to find the best tour of the ball's total distance touching all columns. This task mimics what the surgeon will need to do in Laparoscopic surgery. As mentioned earlier, this is symmetric TSP since $d_{ij} = d_{ji}$ for each pair of columns, where $i \ne j$. Due to the $\Delta - ineq$ property, it can be said that there exists a TSP optimal solution that can be formalized as the search for a Hamiltonian tour of minimum cost in a complete directed graph $G =$ (V, A) [17,19].

Nation and Parameters

- i, j: indices on set V of columns
- d_{ij}: distance from column i to j.

Variables

- For each $i, j \in V$ *and* $i \neq j$, Let x_{ij} be a binary decision variable where $x_{ij} = \begin{cases} 1\ if\ the\ bead\ travels\ directly\ from\ i\ to\ j \\ 0\ otherwise \end{cases}$

The Mathematical Model Formulation [15]

$$Minimize \sum_{(i,j)\in E} d_{ij}x_{ij} \tag{1}$$

Subject to

$$\sum_{i\in V:(i,j)\in E} x_{ij} + \sum_{i\in V:(j,i)\in E} x_{ji} = 2, \quad j \in V \tag{2}$$

$$\sum_{(i,j)\in E:i\in S,\ j\notin S} x_{ij} + \sum_{(j,i)\in E:i\in S,\ j\notin S} x_{ji} \geq 2, \qquad S \subset V, \quad 2 \leq |S| \leq \frac{|V|}{2}$$
$$x_{ij} \in \{0,\ 1\}, \quad (i,j) \in E \tag{3}$$

The objective function (1) minimizes the total distance traveled from one column to the next within the potential tours. Constraint (2) guarantees that each column is visited once, which means that the column should receive the ball once and send it to the next column once. However, constraint (2) does not guarantee to fall into the sub-tours trap. For example, a sub-tour that may result which satisfying constraint (2) is 1–2–1. Thus, constraint (3), known as connectivity constraint, is added to eliminate any sub-tour of size equal to the total number of columns divided by 2.

Results and discussion

The mathematical model of the Ball-Clamping module problem was solved using **AMPL**. A Mathematical Programming Language, known as AMPL, is an algebraic modeling language used to describe and solve high-complexity problems for large-scale mathematical computing. The reason for using the AMPL software is that it maintains the ability to change the data/inputs easily without modifying the model itself. The AMPL code used is adopted from [20]. After the mathematical model has been solved, the optimal tour with a minimum travel distance is obtained, as shown in Fig. 3(a).

Fig. 3(a) shows the optimal tour the ball travels, starting from column 1 and ending in the same column with a minimized total travel distance equal to 143.31 cm. The optimal travel route of the ball from one column to another is 1→13→10→14→11→12→15→9→8→5→4→6→7→2→3.

This tour is the best for the minimum time needed to traverse through all corresponding surgery points. It supports the physician's referring to this as the shortest and best path when performing the surgery.

The iterations were explored as they were happening by applying the AMPL code without the sub-tours elimination constraint (3). Fig. 3(b) shows the impact of not considering the sub-tours elimination constraint in generating sub-tours. This Figure also presents the first iteration obtained from the matrix resulting from AMPL.

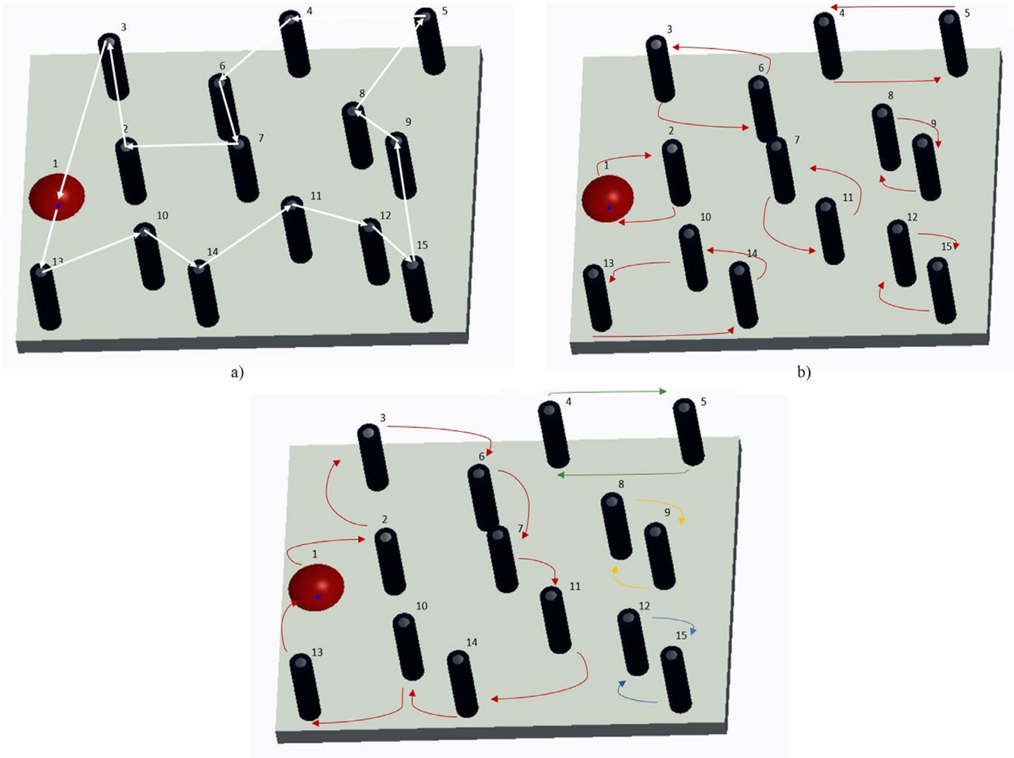
Applying the sub-tour elimination constraint and repeating it for each iteration will eliminate each sub-tour until they are connected to one optimal tour. The sub-tour elimination constraint was added to the AMPL code to remove sub-tours, such as those shown in Fig. 3(b). The relationships are updated according to the AMPL displayed matrix, as shown in Fig. 3(c).

Fig. 3(c) illustrates how the solution evolves until the final best tour is obtained. After improving the first sub-tour using the sub-tour elimination constraint, this sub-tour resulted from the second iteration.

Sensitivity analysis study

The sensitivity analysis aims to show the robustness and applicability of the developed model in responding to different types and settings of trainee boxes. The reason for conducting a sensitivity analysis is to measure the impacts of changing the number of columns on the trainee's performance and practice. Table 2 presents the outcomes of this study in terms of the shortest distances associated with their optimized tour path versus other numbers of nodes (columns).

Table 2 shows that this model is applicable for different box types and setups in terms of the number of columns, as it is just the data scale that is different from being fed into the model. The shortest distance and tour sequences depend on the number and locations of columns added or removed. Thus, it is not straightforward to build an intuition or a pattern for the effect of adding or removing columns from the box. Comparing the obtained results (143.31 cm) and the sensitivity analysis output shows that removing nodes minimizes the total distance as expected (124.36 to 139.86 cm). This validates the results, and from another perspective, it justifies how changing the number of columns would impact the total distance. One final note is that the total distance decreases slowly with more nodes removed.



a) b)

c)

Fig. 3. (a) Optimal tour the ball travels (b) The first iteration, no sub-tour elimination constraint was applied (c) Impact of the Sub tour elimination constraint.

Table 2
Sensitivity analysis (Tours resulted from removing/adding columns).

Node Removed	Shortest Distance	Tour
8	139.86 cm	1 -> 13 -> 10 -> 14 -> 11 -> 12 -> 15 -> 9 -> 5 -> 4 -> 6 -> 7 -> 2 -> 3 -> 1
4,8	135.52 cm	1 -> 2 -> 3 -> 6 -> 7 -> 5 -> 9 -> 15 -> 12 -> 11 -> 14 -> 10 -> 13 -> 1
4, 8, 12	135.21 cm	1 -> 2 -> 3 -> 6 -> 7 -> 5 -> 9 -> 15 -> 11 -> 14 -> 10 -> 13 -> 1
4, 8, 12, 14	130.46 cm	1 -> 13 -> 10 -> 7 -> 11 -> 15 -> 9 -> 5 -> 6 -> 3 -> 2 -> 1
2, 4, 8, 12, 14	124.36 cm	1 -> 3 -> 6 -> 5 -> 9 -> 15 -> 11 -> 7 -> 10 -> 13 -> 1
Node Added	Shortest Distance	Tour
16	140.61 cm	1 -> 13 -> 10 -> 14 -> 11 -> 12 -> 15 -> 9 ->8 -> 16 -> 5 -> 4 -> 6 -> 7 -> 2 -> 3 -> 1
17	142.05 cm	1 -> 13 -> 10 -> 14 -> 17 -> 7 -> 11 -> 12 -> 15 -> 9 ->8 -> 16 -> 5 -> 4 -> 6 -> 3 -> 2 -> 1
18	147.75 cm	1 -> 13 -> 10 -> 14 -> 17 -> 7 -> 11 -> 12 -> 15 -> 18 -> 9 ->8 -> 16 -> 5 -> 4 -> 6 -> 3 -> 2 -> 1

Conclusion and future work

In this study, TSM is proven to be a successful feedback tool in Laparoscopic training and other training modules and surgical tasks to evaluate the quality of the trainee's performance after the exam is completed. The aim was to provide the best performance possible in feedback to enhance and assess the participants' skills. The classical TSM was utilized to generate the shortest distance tour for a single box clamping model, as this type of box was the focus of this study.

The model was implemented to generate the shortest distance tour for a single box climbing model, as this type of box was the focus of this study. The results can be embedded in the box using a simple screen to show the best route with a minimum tour distance, which can be used as a reference for the trainees.

The contribution of this work was to extend the implementation of the TSP and its classical mathematical modeling formulation and utilize them in a specific and critical surgical healthcare problem. However, this model does not apply to other realistic settings such as anatomy, the difficulty of passing from a node and using a non-dominant hand.

In future work, the above realistic settings need to be incorporated into the TSM, suggesting that the solution could also be implemented in other surgical tasks in the same fashion used to solve the Ball Clamping module. Also, the results can be embedded in the box using a simple screen to show the best route with a minimum tour distance, which can be used as a reference for the trainees. Other realistic settings, such as anatomy, the difficulty of passing from a node to another, and using a non-dominant hand, could be incorporated as future work.

Ethics statements

The work doesn't involve animal or human subject. Additionally, there is no data from social media platforms involved in the work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mohammad A. Shbool: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Ammar Al-Bazi:** Validation, Conceptualization, Writing – original draft, Writing – review & editing. **Alma Kokash:** Software, Methodology, Writing – original draft, Writing – review & editing. **Wafa' H. AlAlaween:** Writing – review & editing. **Nibal T. Albashabsheh:** Writing – review & editing. **Raed Al-Taher:** Validation, Writing – review & editing.

Data availability

Data used in this research is included in the article.

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