Redesigning the Medical Examination Table for Improved Accessibility

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Abstract

Healthcare accessibility remains a significant challenge for patients with mobility impairments, exacerbated by structural barriers in clinical environments. Traditional medical examination tables, often fixed-height and lacking intuitive adjustability, hinder thorough assessments and contribute to delayed or forgone care. To address these issues, we developed a novel, manually adjustable medical examination chair that transitions into an examination table while maintaining affordability and ease of use. Our design incorporates a scissor lift base, a manual worm gear mechanism for height adjustment, and a ball screw linear actuator for reclining functionality, eliminating reliance on expensive electronic components. A cost-benefit analysis guided the selection of materials, ensuring durability and clinical suitability while maintaining a target budget of $800–900. Additionally, we surveyed healthcare providers to assess usability concerns with standard examination tables and evaluate the perceived necessity of accessibility-focused improvements. Statistical analyses of survey responses revealed significant interactions between specialty and the percentage of mobility-impaired patients seen ($p = 0.00513$) regarding positioning challenges. The findings highlight the need for accessible, cost-conscious medical equipment and inform future design iterations of our design. By prioritizing practical functionality, our proposed examination chair aims to enhance provider efficiency and improve patient experience while contributing to broader healthcare accessibility efforts.

Keywords: medical examination table, healthcare, accessibility, mobility-impaired persons

Introduction

In the United States, more than one in four adults (28.7%) live with some form of disability, with 12.2% experiencing a mobility disability that significantly impacts their ability to walk or climb stairs[1]. People with disabilities frequently report unfavorable consequences after experiencing unfair treatment in healthcare settings, often at higher rates than adults without disabilities. Approximately 71% of people with disabilities who encountered discrimination in healthcare settings reported disruptions in their care, including 54% indicating delaying necessary care and 50% forgoing it altogether[2]. Traditional examination tables are typically fixed at a height of 32", presenting accessibility challenges for mobility-limited patients, often resulting in a lack of thorough examination[3]. In addition to accessibility challenges, the current examination table has raised concerns of durability and cleanability, especially after the COVID-19 pandemic.

Dr. Masahiro Morikawa, a practicing Family Medicine doctor at the University of Virginia (UVA) primary care facility, asked our team to continue a project he proposed: redesigning the examination table for accessibility and efficiency. A majority of the examination tables within his department were 32" fixed-height tables that were difficult for patients, notably older patients and those with mobility disabilities, to use. The department did have a powered accessible examination chair, but Dr. Morikawa stated the controls were unintuitive, the design was bulky, and the electronics were limiting for practices with less resources. He was also unimpressed with the prices of both the fixed-height and powered exam tables, which cost his practice thousands, and believed a design with minimal electronics would be most affordable. This led him to offer the project to capstone students several years ago, to address these main issues.

A preliminary design was created by a former capstone team, which focused on the chair surfaces and force simulations for their design (**Fig. S1**). Our group's goal was to create connector pieces and design systems to facilitate movement. However, before we could add to the project, the previous design required some modifications. The former team initially designed it to house several electronic components, which would significantly increase the cost of the chair. Files for 3D parts, research, and calculations were not provided in the project handoff. To continue the project, we would first have to recreate the chair surfaces dimensioned by the previous team and redesign the lift system to reduce the number of electronic and hydraulic components used. During an initial discussion of constraints and project goals, our advisor asked us to prioritize affordability and ease of use for the practitioner. We additionally wanted to focus on patient comfort by adding supportive and padded seats, and aimed to collect feedback from providers on our proposed design.

The goal of our project was to create a 3D assembly of an accessible examination chair that used manual mechanisms to transition into an exam table capable of holding 300 lbs. patient weight. The design would follow the guidelines required by the Standards for Accessible Medical Diagnostic Equipment, including rising from a transfer height of 17” to an examination height of 32”. When raised, the chair and leg sections would recline to be used as an exam table. To reduce the final price and for the chair to be usable in limited-resource settings, minimal electronic and hydraulic components would be used. Sufficient padding would be used in the seat cushions to provide patients support and comfort, with surfaces that were easy to disinfect between visits and could withstand the cleaning agents used in a medical setting. We also performed a price estimation, with a target budget of $800 - 900 for the proposed design. Partway through the design process, we were also asked to include a mechanism to add swiveling functionality, to allow for greater patient manipulation. To identify additional issues with the current standard exam tables and gather diverse user feedback, we conducted a survey of UVA healthcare providers. The survey aimed to explore whether healthcare providers with different specialties, years of experience, and percentages of mobility patients seen would have differing opinions on the usability and functionality of exam tables. The test hypothesis states that healthcare providers with different specialties, years of experience, and percentages of mobility patients seen will have differing responses to the usability and functionality of a novel medical examination chair. Conversely, the null hypothesis states that there is no significant difference in survey responses regarding the usability and functionality of the examination chair across doctors’ specialties, years of experience, or percentages of mobility patients seen.

Results

Mechanisms Modeling

The scissor lift table served as the base for each of the mechanisms and the chair itself. It consists of 2 parallel plates that can raise and lower by decreasing or increasing the distance between the 2 crossed arms on either side. Five connecting rods fit into holes and slots to provide support between the arms and the plates (**Fig. 1**). These parts (one plate, one arm, and one connecting rod) were modeled as parts in SOLIDWORKS, a computer-aided design (CAD) program. An assembly was created from these base parts and mated within the software to emulate the device’s range of motion in real life. The table was designed to raise from a height of 12” to 30”, allowing for the height of the turntable and chair seat installed on top of it. The surface of the seat would rise from the standard transfer height to the examination height, 17” and 32” respectively with allowances for design changes should future designers add more components between the seat and tabletop. The plates and lift arms would be cut from the same sheet of 304 stainless steel to save on manufacturing costs, sharing a thickness of 0.375”. The plates were designed to be bent from these cut pieces. Similarly, the 5 connector rods would be machined from the same round bar of cold-rolled 1144 carbon steel with a 1” diameter. This mechanism was preferred over the previously proposed hydraulic system, since it does not require a hydraulic component to operate. Construction lifts, scissor lift carts, and other accessible exam table designs utilize scissor lifts, though they are often paired with hydraulic or motorized attachments to assist lifting heavy loads. Microscopes, which served as the main inspiration, pair these lifts with rack and pinion gears to raise and lower their stages.

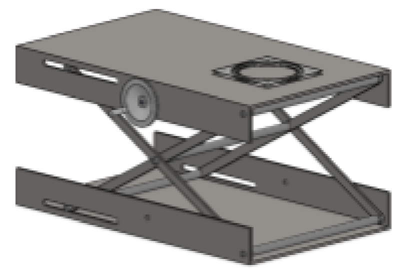

Figure 1: *Scissor Lift Table*

The worm gearbox acted as the raising and lowering (high-low) mechanism driving the scissor lift. The gearbox was positioned underneath the top plate of the scissor lift, with the hand wheel connecting from the outside through a hole cut 17.5” from the front of the table. This wheel drives two spur gears (gears 1 and 2) with a 1:4 ratio, which in turn drives a worm gear. The worm gear drives another set of spur gears in a 1:5 ratio (gears 3 and 4). The last spur gear slides a rack horizontally which is coupled to a connector rod, pushing and pulling the rod to allow for the raising and lowering of the scissor lift (**Fig. 2**). By turning the hand wheel once clockwise, the scissor lift table would raise 1”; turning the wheel counterclockwise would lower the table by 1”. A worm gear was chosen for its unique self-locking property utilized by rack and pinion jacks; the worm gear cannot be driven by gear 3, meaning forces pushing the surface of the table down cannot cause the table to lower. The layout and design of the gearbox was inspired by thang010146’s video and downloadable SOLIDWORKS assembly[4]. The gears, hand wheel, and rack were used off-the-shelf (OTS) components downloaded from McMaster-Carr while the layout and plastic housing were original creations.

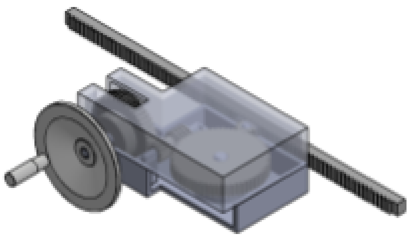

Figure 2: *Worm Gearbox*

The turntable mechanisms allowed for limited rotation of the chair on top of the scissor lift table. The design was inspired by an OTS part from McMaster-Carr, with additional features to limit how far the attached seat can turn. The bottom plate has a single central protrusion facing the front of the turntable and the top plate has two protrusions angled 50° out from the center. When rotated, the collision of the central and side protrusions limits the range of motion. The 304 stainless steel plates encapsulate 66 ball bearings with ⅜” diameter, a common size that can be ordered easily (**Fig. 3**).

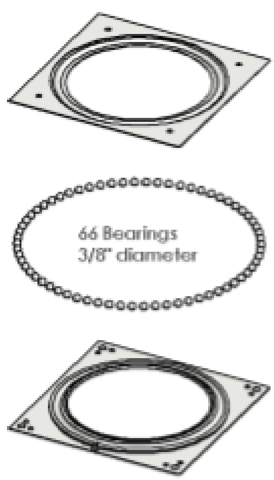

Figure 3: *Exploded view of turntable*

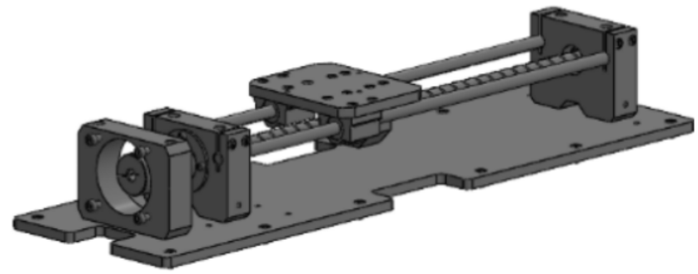

Figure 4: *3D Model of Ball Screw Linear Actuator*

The ball screw linear actuator reclining mechanism was successfully 3D modeled (**Fig. 4**). The design enables reclining from a 90-degree upright position to a fully flat 180-degree position. The mechanism operates by rotating a screw through a manual crank gear system, which in turn moves a traveling nut along the threaded shaft. The nut is connected to the backrest frame via a positioning arm, causing it to move smoothly and securely as the crank is turned. The entire mechanism is housed beneath the seat, which keeps the chair compact and prevents visual or structural bulkiness. Some light research was done on chair framing to determine whether the reclining mechanism would be able to securely fit into the chair as planned. It was found that a similar framing structure to reclining chairs would be suitable for this new exam chair. But, instead of wood, we would be using medical grade austenitic stainless steel. Key design parameters were calculated based on estimated loading conditions. The expected axial load was 350 pounds, accounting for a 300-pound patient and a 50-pound backrest. The stroke length of the actuator was set at 10”, with an acceptable tolerance of ±0.25”. A C7-grade ball screw was selected for its balance of cost and availability, with an outer diameter of 30 mm and a lead of 2”. This setup is expected to provide a linear speed of approximately 1 inch per second when manually cranked at 25–30 RPM. A simple 1:2 or 1:3 gear ratio was proposed to reduce the force needed for cranking while maintaining practical reclining speed. This gearing system connects the manual crank to the moving end of the ball screw. The expected service life of the mechanism was estimated at 20,000 hours, which is more than enough for this application.

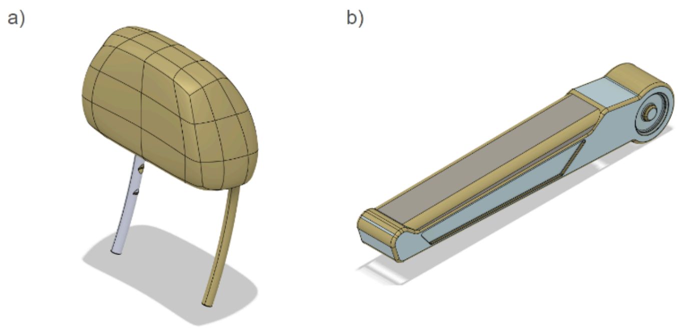

Figure 5: *3D Models of the (a) Headrest and (b) Armrest.*

The modeled headrest incorporated a dual-rod vertical insert system with a groove-locking mechanism, allowing for adjustable height while ensuring stability (**Fig. 5a**). The armrest was designed to snap into a matching socket mounted on the chair back (**Fig. 5b**). It can be rotated to either a vertical or horizontal position to improve patient entry and overall comfort. It was also imperative that we had a baseline model for the chair seat and chair back to base the mechanism sizing from. We were able to successfully replicate the chair seat (**Fig. S2a**) and back (**Fig. S2b**) that the previous capstone team designed.

After the individual components were modeled, they were compiled into subassemblies for each mechanism: turntable, worm gearbox, linear actuator, and scissor lift. These were later joined in a master assembly of the whole chair (**Fig. S3**). Parts modeled in Fusion 360, another CAD program, were imported into SOLIDWORKS as .STEP files, with parts designed in SOLIDWORKS and downloaded from McMaster-Carr kept as their native .SLDPRT files.

Chair Materials and Cost-Benefit Analyses

A cost-benefit analysis was conducted to evaluate the total cost of key materials used in the construction of a medical examination table. Polyvinyl chloride (PVC) was selected for the upholstery due to its durability, ease of cleaning, and resistance to bacterial growth, which are essential characteristics for medical equipment used in clinical settings. Modern examination tables often feature PVC covers because of their ability to withstand repeated cleaning with bacteria-killing solutions without degrading. The material is also easy to maintain, which ensures that the exam chair remains hygienic over long periods of use. PVC is also an eco-friendly alternative that emits no off gassing[5]. The cleanability of PVC is crucial for maintaining a sterile environment. The Relative Light Units (RLU) value, a measure of microbial contamination, with a marginally acceptable RLU value, is between 100 and 300 should be ≤ 150[6]. PVC's RLU values typically fall within this ideal range. From a cost perspective, PCV, which covers 2,123.988 in^2 of material, was sourced from Carolyn Fabrics and amounts to $29.77.

Ethylene-vinyl acetate (EVA) foam was chosen for the padding due to its excellent cushioning properties, shock absorption, and durability. EVA foam is a closed-cell material known for its shock-absorbing qualities, making it ideal for applications that require patient comfort during prolonged usage[7]. The foam density typically ranges from 40 to 60 kg/m^3, providing a balance of comfort, support, and durability, which makes it an ideal choice for healthcare applications[8]. EVA is designed to hold enough patient weight of about 300 pounds, making it suitable to accommodate a wide range of patients. Additionally, EVA foam is water resistant, which is critical for maintaining hygiene in medical environments. The foam is firm enough to support patients without compromising on comfort, and its resistance to UV radiation ensures that it retains its structure over time[9]. The cost of EVA foam was calculated based on the amount needed to achieve the desired thickness of 4". For this application, 4,247.976 in^3 of EVA foam were sourced from Worldwide Foam at a cost of $206.70 per sheet, including a $150 handling fee. Given the dimensions and density of the foam, the total cost of EVA foam for the chair's padding amounts to $197.63.

The framework of the chair would be made from 304 Austenitic stainless steel, a material selected for its exceptional strength, corrosion resistance, and long-lasting durability in clinical environments. The 304 grade contains 18% chromium and 8% nickel, making it highly resistant to oxidation and corrosion, as it can withstand harsh cleaning processes and is resistant to corrosion[10]. The tensile strength is a minimum of 515 MPa, and it typically reaches 625 MPa, ensuring that the material can withstand substantial forces without failing[11]. The yield strength is typically around 205 MPa, indicating the stress at which the material will begin to deform permanently[12]. Additionally, the material has a ductility with an elongation at break range from 45% to 70%, which allows it to absorb energy and undergo plastic deformation without fracturing[13]. The modulus of elasticity, which measures the material's ability to return to its original shape after being deformed, ranges from 193 to 200 GPa, providing excellent stiffness and structural support[14]. The cost of the required amount of 304 stainless steel, which weighs 621.66 kg, was sourced from North American Stainless at $1.3928 per pound. The total cost of the framework material, including surcharges, amounts to $532.02.

The combined total material cost amounts to **$759.42** (**Tab. 1**).

Material	Source	Units	Material cost/unit	Total cost
Upholstery: Polyvinyl chloride (PVC)	Carolyn Fabrics (Highpoint, NC)	2123.988 in^2	$27.25/linear yard*	$29.77
Padding: Ethylene-vinyl acetate (EVA)	Worldwide Foam (Elkhart, IN)	4247.976 in^3	$206.70/sheet**	$197.63
Frame: 304 stainless steel	North American Stainless (Wrightsville, PA)	621.66 kg	$1.3928/lbs***	$532.02
			Total cost:	**$759.42**

* of a 54'' wide fabric
**2 lb EVA 4in x 48in x 96 in + $150 handling fee
***Austenitic, 14 gauge, 2'' x 2'' rectangular tube + $79.44 surcharge + $59.84 base charge

Table 1: *Completed Material Cost Estimation*

This represents the cost of the core materials needed to construct the medical examination chair, which is a reasonable investment considering the durability, comfort, and ease of maintenance that these materials offer. For the manufacturing cost analysis of our medical examination chair, we focused on obtaining estimates for labor and overhead costs from various manufacturers and distributors. While we were able to successfully determine the material costs for the chair, estimating the manufacturing costs, including labor and overhead, proved to be a challenge due to restrictions imposed by manufacturing companies. Representatives from companies like USA Med Bed, LLC, and Henry Schein Medical explained that they could not provide pricing details as they typically sell to medical and dental professionals with business affiliations. Some manufacturers, such as Clinton Industries and Oakworks, advised that pricing information was available only through distributors, who handle the sales of the tables. To estimate labor and overhead costs more broadly, we conducted a general search and found that labor costs for manufacturing manual exam tables are typically in the range of $200 to $300. Based on this rough estimate, the total manufacturing cost for our redesign was projected to be approximately **$1,100**. This estimate includes both the material costs, which we have already determined, and the estimated labor and overhead costs.

Survey and Statistical Analysis

The survey distributed to healthcare professionals produced useful feedback. Respondents highlighted a need for improved adjustability and greater support for patients with mobility impairments. For Q1, "My practice would be benefited by having more physically accessible medical examination tables," the bar chart result in **Figure 6** indicates a strong inclination among healthcare providers that a more accessible examination table would be beneficial for their practice. A small number of respondents chose lower scores, indicating that while there is widespread support for the concept, there is some variability in the perceived need for examination tables. However, the results of the ANOVA showed there was no significant effect of specialty ($p = 0.288$), years of experience ($p = 0.809$), or percentage of mobility-impaired patients seen ($p = 0.632$) on the responses. Furthermore, no significant interactions were observed between specialty and years of experience ($p = 0.875$), specialty and percentage of mobility-impaired ($p = 0.108$), or years of experience and percentage of mobility-impaired patients seen ($p = 0.521$). Therefore, the null hypothesis that there is no significant difference in responses is not rejected.

For Q2 (**Fig. 6**), "My practice has considered purchasing electric-powered medical exam chairs that provide more physical accessibility for patients, but this option was too expensive to implement," the bar chart distribution is notably skewed, as 16 out of 31 respondents were neutral, indicating that price of electric-powered exam chairs was a significant concern, but not one that completely deterred interest. Fewer respondents chose the extreme ends of the scale, suggesting that while some healthcare providers acknowledge the cost barrier, it may not be the only factor influencing their decision to purchase such chairs. The ANOVA results revealed a significant effect of years of experience (**$df = 3$, $f = 4.633$, $p = 0.0188$**), indicating that healthcare providers with different levels of experience perceived the cost of electric-powered exam chairs differently. However, there are no significant effects for specialty ($p = 0.1529$), percentage of mobility-impaired patients seen ($p = 0.4615$), or the interactions between these factors (all $p > 0.05$). Post-hoc tests using Tukey's HSD showed the largest difference in responses was between healthcare providers with 6-10 years of experience and those with 16+ years of experience. This difference between these two groups was marginally significant with an unadjusted p-value of 0.0906, but after multiple comparisons correction (adjusted p-value 0.09), this difference was no longer statistically significant. Additionally, there were no other significant differences between the other groups based on years of experience. These results suggest that while cost is a concern, it does not significantly vary across different specialties or the percentage of mobility-impaired patients seen, and the null hypothesis was not entirely rejected.

For Q3 (**Fig. 6**), “If physically accessible medical examination chairs were half the cost as they are now (~$1,100 per table), my practice would consider purchasing them,” the bar chart shows that 13 out of 31 responders selected a Likert score of 3 (neutral) indicating uncertainty about whether the reduced cost would influence their purchasing decision. A smaller portion selected 4 (agree) or 5 (strongly agree), while some selected lower scores, reflecting that the price may not be the primary factor in their decision. The three-way ANOVA revealed no significant differences across the three factors in terms of willingness to purchase the chairs at a reduced price. Specifically, none of the main effects or interactions were statistically significant (all p-values > 0.05), suggesting that these factors did not influence responses to the question. Thus, the null hypothesis was not rejected.

For Q4, “The material on the current standard medical examination table where patients sit or lay down is easy to clean between patients,” the bar chart (**Fig. 6**) indicates that the respondents rated the ease of cleaning highly, with 11 out of 31 selecting 4.5 (agree) and 12 out of 31 selecting 5 (strongly agree). A smaller number selected lower scores, reflecting some concerns about cleaning, but suggesting that it is generally not a major issue for most providers. Statistical analysis showed no significant effects for specialty ($p = 0.288$), year of experience ($p = 0.943$), or percentage of mobility-impaired patients seen ($p = 0.627$). There were also no significant interactions between these factors (all $p > 0,05$). The results suggest that the perceived ease of cleaning does not significantly vary across the three tested factors. Therefore, the null hypothesis was not rejected.

For Q5, “I have no patient positioning issues when performing all necessary medical exams at my practice using the current standard medical examination tables,” the bar chart (**Fig. 6**) shows that 13 out of 31 respondents selected 2 (slightly disagree) and more respondents on the lower scale, suggesting there is a notable portion indicating patient positioning issues on the current standard exam tables. The ANOVA results indicated a significant interaction between specialty and percentage of mobility-impaired patients seen (**$df = 2$, $f = 7.869$, $p = 0.00513$**), suggesting that these factors together significantly influenced responses. However, there was no significant main effect for specialty ($p = 0.24781$), years of experience ($p = 0.14157$), years of experience ($p = 0.14157$), or percentage of mobility-impaired patients ($p =$

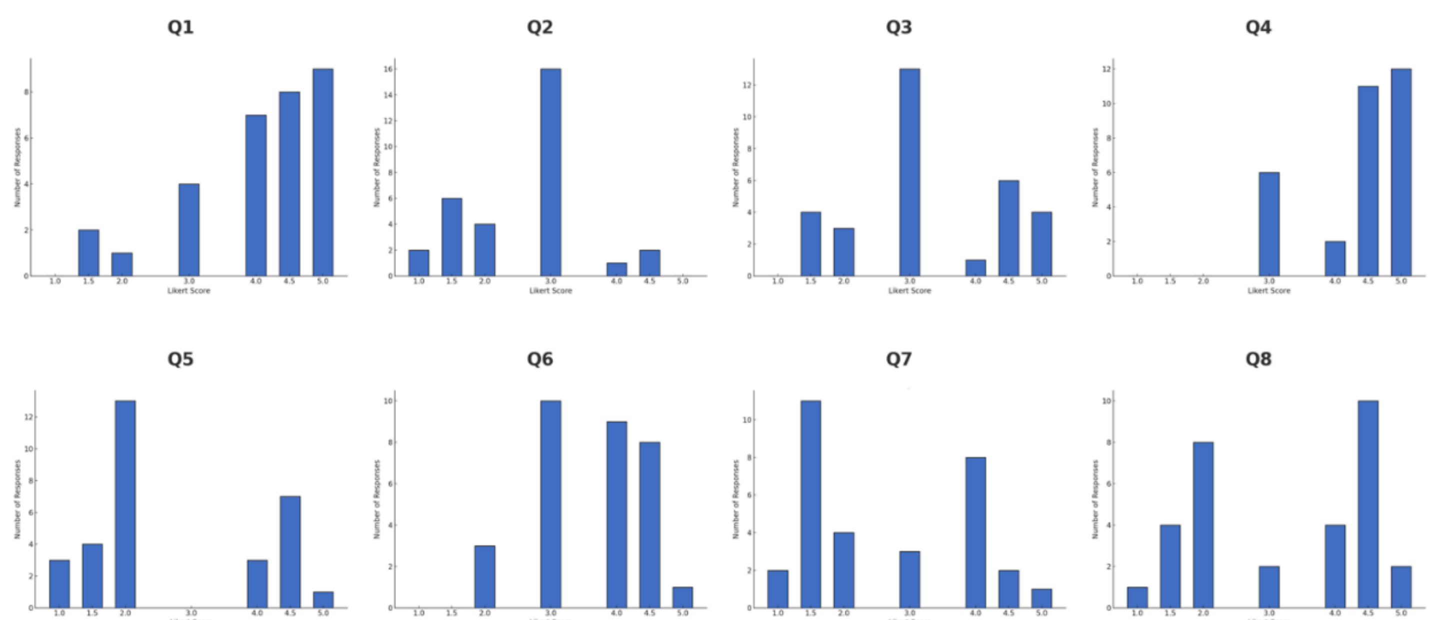

Figure 6: *Bar charts showing distribution of healthcare provider responses (Q1-Q8) evaluating features of a redesigned medical examination chair. Each chart illustrates specific survey question for each Likert score (1 = strongly disagree to 5 = strongly agree), providing insight into provider preferences and perceived benefits across different aspects of the chair design.*

0.0659). Post-hoc Tukey's tests revealed several pairwise comparisons, showing that healthcare providers with 0-25% mobility-impaired patients in specialties like Orthopedics and OB-GYN (adjusted p value 0.9576) had significantly different positioning issues compared to those in Family Medicine and Urology, especially when considering their mobility patient percentage. However, many of the comparisons did not reach statistical significance after applying multiple comparison corrections. Given the significant interaction between specialty and percentage of mobility-impaired patients seen, the null hypothesis was partially rejected. The significance was not uniform across all comparisons, and many differences were not statistically significant after adjusting for multiple hypotheses.

For Q6, "Patient positioning would be better if the patients were able to be moved while on the medical examination table instead of me walking around the table," the bar chart (**Fig. 6**) illustrates 18 out of 31 respondents selected higher on the Likert scale, suggesting that most healthcare providers believe that patient positioning could be improved with more mobility accessible examination tables. The ANOVA showed no significant effects for specialty ($p = 0.405$), years of experience ($p = 0.585$), or percentage of mobility-impaired patients ($p = 0.585$) and no significant interactions between the factors (all $p > 0.05$). Perceptions about the ability to move patients on the examination table are not significantly influenced by the factors, and therefore, the null hypothesis is not rejected.

For Q7, "My patients often complain about the comfortability of the standard examination table in my practice," the bar chart (**Fig. 6**) results show that 11 out of 31 respondents selected 1.5 (slightly disagree) and 8 out of 31 respondents selected 4 (slightly agree), suggesting that most providers do not receive frequent complaints about the comfort of the standard examination chair. The ANOVA results showed no significant interactions between specialty ($p = 0.535$), years of experience ($p = 0.448$), or percentage of mobility-impaired patients ($p = 0.969$), thus rejecting the null hypothesis.

Lastly, for Q8, "Overall, I have little to no issues with using the standard medical examination tables in my practice," the bar chart (**Fig. 6**) shows 10 out of 31 responders selected 4.5 (agree), with fewer respondents selecting extreme scores (1 or 5). This suggests that while many healthcare providers generally have few issues with using the standard examination tables, a portion still experiences some concerns. ANOVA results showed no significant effects for specialty ($p = 0{,}591$), years of experience ($p = 0.567$), or percentage of mobility-impaired patients seen ($p = 0.356$). There were no significant interactions between these factors (all $p > 0.05$); therefore, not rejecting the null hypothesis.

Discussion

Interpretation of Results

The final selection of mechanisms used in our design was driven by a balance of functionality, simplicity, and user accessibility. For the reclining mechanism, we initially decided to use a lead screw linear actuator. The reason we ended up choosing the ball screw linear actuator, even though it can be more pricey, is because of its smoothness in reclining motion and extremely low maintenance. Similarly for the worm gearbox, the initial design omitted two gears that greatly reduced the number of turns needed to raise the table and their inclusion makes the design easier for provider use. The turntable and its swivel functionality also were not planned but felt necessary for our design since it made patients easier to move, by their own volition or the providers'. Although motorized systems are common in medical settings, the proposed design demonstrates that mechanical alternatives can deliver similar functionality at lower cost and with simpler maintenance. The use of widely available components and standard frame construction methods also supports long-term durability and manufacturability.

To ensure we created a design for eventual manufacturing, we created parts with dimensions based on easily available raw materials and OTS components. Using these standard materials and dimensions would reduce the number of custom components that would eventually be manufactured, reducing the eventual price of the complete chair and making the parts easily replaceable should they break. The steel supplier website Ryerson provided standard metal plate thicknesses, round bar diameters, and parameters for width and length of steel products. OTS components (gears and ball bearings) were chosen from the McMaster-Carr online catalogue, which offers a wide range of industrial products. Each part has an associated SOLIDWORKS file available for download, which we used to insert the components into our assembly instead of recreating them to ensure accuracy.

The material cost-benefit analysis for the medical examination chair demonstrated that the selected materials, PVC for the upholstery, EVA foam for padding, and 304 austenitic stainless steel for framework, offer a balance of cost-effectiveness, durability, and performance in a clinical setting. PVC provides a low-cost, easy-to-clean surface, essential for maintaining hygiene, although its longevity can be limited if not maintained properly. EVA foam offers excellent cushioning and durability, with the ability to support a weight capacity of around 300 pounds. 304 stainless steel provides exceptional strength, corrosion resistance, and long-term durability, ensuring the chair's structural integrity in clinical environments.

The survey results revealed key insights into healthcare providers' views on medical examination tables. Respondents supported the need for more accessible tables, although statistical analysis showed no significant difference across specialties, years of experience, or the percentage of mobility-impaired patients seen. This suggests that the perceived need for accessible tables is widespread, but not strongly influenced by these factors. For Q2, in the case of electric-powered examination tables, years of experience of 6-10 years and 16+ years appeared to influence perceptions of cost; post-hoc testing showed that the difference between experience groups was not statistically significant after multiple comparisons. The sample size may be too small to detect meaningful differences, and there may be high variability in responses within each group. Additionally, the effect of experience on cost perceptions might be marginal, and adjustments for multiple comparisons reduced the threshold for significance.

When addressing patient positioning issues, in Q5, a significant interaction between specialty and percentage of mobility-impaired patients was found. Healthcare providers who treat 0-25% of mobility-impaired patients reported having more positioning issues. Post hoc revealed the effect varied across specialties of Orthopedic and OB-GYN. Orthopedic specialists often treat patients with significant mobility impairments, joint issues, or injuries that require frequent repositioning during exams, making accessible tables crucial for both patient comfort and exam efficiency. Additionally, OB-GYN works with those in pregnancy or routine gynecological care requiring frequent pelvic exams, so positioning patients on a user-friendly chair is also a need in this specialty.

Significance and Innovation of the Project

Existing solutions on the market predominantly rely on motorized mechanisms, making them prohibitively expensive for widespread implementation, particularly in smaller clinics and resource-limited healthcare settings. Standard fixed-height tables, while more affordable, fail to accommodate patients who require transfer assistance, limiting provider flexibility and compromising thorough examinations. Our project aims to bridge this gap by developing a manually adjustable, cost-effective examination chair that prioritizes accessibility without relying on expensive electronic components. By integrating intuitive manual mechanisms, such as a worm gear-driven scissor lift and a ball screw linear actuator for reclining, our design ensures ease of use while maintaining affordability. This innovation not only enhances patient access but also addresses provider frustrations with existing equipment, ultimately supporting more inclusive and adaptable healthcare practices.

Limitations

Originally, our project aimed to complete the following: design and create a functional 3D model of a high-low examination chair that can support up to 300 lbs. and recline into a table position, optimize material selection, manufacturability, and material cost-benefit analysis, and survey healthcare providers across a variety of practices to assess overall issues providers have with current examination tables. These project goals changed while working on them because our mechanical mechanism research took a lot longer than anticipated. We were unable to start 3D modeling for a leg positioning mechanism and the proposed manual crank and gear train used to power the reclining mechanism. We were also unable to create a complete model of the chair and conduct force simulations on our modeled mechanisms.

It was also not feasible to receive manufacturing cost quotes from vendors due to company policy. We were told that quotes cannot be given to persons who are not associated with a business. Without access to real manufacturing data or vendor quotes, our cost analysis relied on approximations and publicly available pricing for components and materials. This limited our ability to create a fully accurate budget or evaluate the commercial viability of the chair in a real-world production setting. Additionally, the absence of detailed feedback from manufacturers meant that certain design elements, particularly those involving fabrication complexity, could not be fully evaluated for scalability or mass production.

Implications for Future Design Iterations

The importance of accessible medical diagnostic equipment has long been dismissed. The education - or lack thereof - providers receive in medical school promotes the ideology that those with disabilities must be cured of their "handicaps" instead of accepted and understood as equally abled people in an inaccessible environment[15]. Now, with greater recognition and small legal steps forward, regulations around healthcare accessibility will continue to evolve. Legislation passed in 2024 adopted the *Standards* as enforceable regulations, not just "best practices," in public health facilities. It also outlined purchasing plans of new accessible diagnostic equipment, including examination tables and chairs, and will require a minimum of 1 accessible exam table in appropriate public health facilities[16]. With this requirement, medical facilities will be expected to offer exam tables and chairs that accommodate patients with mobility impairments. Our design addresses several key accessibility gaps in current equipment and has the potential to serve as a cost-effective, compliant alternative in clinical environments. It also provides a cheaper alternative, since a majority of healthcare systems (mostly smaller practices) were reluctant to spend so much when accessible equipment was not a requirement but still an available option. By prioritizing manual operation, adjustability, and transfer ease, our chair represents a step forward in the future of inclusive healthcare design.

Future work is needed to refine our design iteration. All the open-ended feedback we received from providers in our survey has been stored for future design considerations, which future groups can choose to include or expand upon. Additional features, such as the leg supports and stirrups, will need to be designed by future teams. The reclining and high-low systems we created require redesigns to lay out optimal gear ratios and manual crank ergonomics to ensure smooth integration with neighboring mechanisms. Additionally, while the headrest and armrest were successfully modeled, the corresponding mounts on the chair body were not implemented in this design phase, along with the countless connector pieces (screws and bolts) to attach disparate parts together. The completed assembly with these additional features will also need to be tested with force simulations to confirm their viability as a logical option for prototyping. All files - images, calculations, 3D models, etc. - will be made available to future groups to continue the project with no need to recreate previous works. Each step of the process and all design features have been clearly documented for subsequent teams to undertake.

Our project produced a strong foundational design for an improved medical examination chair. With detailed CAD models, clear design rationale, and structured documentation, future teams are well-positioned to carry this project forward toward prototyping and testing. We successfully created a foundation for a more accessible and cost-effective medical examination chair, with detailed design documentation and CAD models that will support future iterations and refinements.

Materials and Methods

Mechanism Design and Modeling

Initial research focused on prior art and mechanical devices to understand their features and identify ways to incorporate them in our design. The Standards outline the requirements for a piece of medical diagnostic equipment (MDE) to be classified as accessible, which influenced our design choices[3]. Existing motorized and accessible medical chairs, construction scissor lifts, and microscope stages were used as inspiration to make the base of the chair a scissor lift table, as well as reclining mechanisms in automobile seats and furniture sets. One insight was to exchange powered components from motorized reclining and lifting systems, since they are simple mechanical systems at their core. The chosen approach for the reclining mechanisms centered on a ball screw linear actuator driven by a manual crank and a basic gear train. Instructional resources and references were used to guide the design, including online videos explaining actuator functionality and ball screw design, as well as the *THK Ball Screw General Catalog* outlining the parts and principles behind linear motion systems[17]. For the high-low mechanisms, a scissor lift table design would be controlled by a worm gear driving a rack and pinion, chosen for its unique self-braking capabilities. Similarly, online videos and downloadable assemblies helped to illustrate the motions of the gearbox, with the *Machinery's Handbook* providing additional information on gear ratios and mounting distance[18]. All mechanical mechanisms described above, including the ball screw linear actuator, gear train, worm gear, and rack and pinion systems, were modeled using SOLIDWORKS to ensure precision, simulate motion, and evaluate feasibility within the overall chair design.

To inform the ergonomic and aesthetic aspects of our chair design, we began by conducting research on automotive headrests and armrests. These components were selected due to their widespread use and established reputation for comfort and support in vehicle seating. The final designs for both the headrest and armrest were directly inspired by automotive counterparts, with an emphasis on shape, contouring, and motion. Using Autodesk Fusion 360, we created original 3D models of a headrest, and one armrest based on our research findings. In addition to these components, the chair seat and chair back were also modeled in Fusion 360. These elements were designed to replicate the visual and structural intent of the final presentation 3D models developed by a previous capstone team. Since no files were provided by the prior group, the seat and backrest were reconstructed through close reference to their presentation.

Material Selection

The process of selecting materials involved a systematic review and evaluation of available options, focusing on cost-effectiveness, durability, and clinical suitability. Initially, research was conducted on the materials currently used in medical examination tables, with particular emphasis on the framework, padding, and upholstery. This research provided a foundation for identifying materials that could potentially meet the specific requirements of the project. Various materials were considered based on critical properties, including density, thickness, mechanical properties, corrosion resistance, and antimicrobial characteristics, to ensure the selected materials would be optimal for a clinical setting.

Once the materials were finalized, a list of suppliers, distributors, and manufacturers for each material was compiled, focusing primarily on companies located on the East Coast and Midwest regions to optimize shipping costs. Supplier selection was also guided by customer ratings and feedback to ensure reliability and quality. We then reached out to these companies either through email or phone calls to obtain detailed price quotes for the materials based on the required dimensions and quantities.

Cost Estimation

After receiving price quotes from several suppliers, we calculated the total material cost based on the unit prices and dimensions determined by the previous capstone team. For the framework, the stainless steel was priced per pound, and the required weight was calculated based on the material volume, while the padding and upholstery were priced per sheet or yard, respectively. Once we gathered all the required pricing information, the material costs were totaled to estimate the overall expense for each component of the medical examination chair (**Fig. S4**).

A similar approach was taken to estimate the manufacturing costs, where we compiled a list of manufacturers and distributors of medical examination tables located primarily on the East Coast and the Midwest regions. These companies were contacted via email or phone to obtain rough estimations of labor costs and manufacturing overhead costs. The gathered information was then intended to be used to calculate an estimated cost of manufacturing, considering factors such as labor rates, machinery usage, and overhead expenses. The final estimates for material and manufacturing costs were then used to assess the overall cost of producing the medical examination chair, which would contribute to the overall feasibility of the project.

Survey and Statistical Analyses

To ensure the new design met real-world needs, a survey was developed and distributed to healthcare providers. The survey included general accessibility and usability questions about current exam tables, along with open-ended prompts to gather additional input. This ensured that our design incorporated both standardized feedback and specific pain points from users in the field. The survey focused on gathering information regarding the accessibility of current medical examination tables in various clinical practices. Specifically, it aimed to assess whether healthcare providers face challenges in patient positioning, the comfort of patients, and the overall functionality of existing tables. The survey also sought to determine the willingness of healthcare providers to invest in more accessible and cost-effective examination tables, with a particular focus on the feasibility of a new, manually adjustable exam chair. The general accessibility and usability questions were structured as Likert-scale questions, which were utilized to assess respondents' agreements with various statements, with scores assigned as follows: 5 points for strongly agree, 4.5 points for agree, 4 points for slightly agree, 3 points for neutral, 2 points for slightly disagree, 1.5 points for disagree, and 1 point for strongly disagree. Open-ended prompts allowed respondents to provide more detailed feedback on the limitations they experienced with current tables and offer suggestions for improvements. The data gathered from Likert-scale questions were analyzed using basic descriptive statistics, while the qualitative responses from the open-ended questions were analyzed thematically to identify recurring concerns and suggestions for future design iterations.

The survey was set up using Qualtrics and distributed via emails sent to department chairs of multiple medical specialties at the UVA Hospital, with a request to forward the survey to the attendings, fellows, residents, medical students, and nursing staff within their departments. These specialties included: Allergy and Immunology, Cardiology, Dermatology, Endocrinology, Family Medicine, Gastroenterology, Surgery, Internal Medicine, OB-GYN, Orthopedic Surgery, Otolaryngology, Rheumatology, and Urology. The survey responses were collected over a period of two weeks. A total of 31 responses were received from the following departments: Cardiology (1 response), Urology (3 responses), Orthopedic Surgery (8 responses), Otolaryngology (1 response), Family Medicine (5 responses), and OB-GYN (13 responses). All survey data was documented in Excel spreadsheets to facilitate data visualizations and statistical analysis.

To analyze the survey data, statistical tests were conducted to evaluate the impact of healthcare providers' specialties, years of experience, and the percentage of patients with mobility impairments on their responses to the survey questions. The primary focus was on understanding whether and how these factors influenced respondents' views on the accessibility and functionality of current medical examination tables. First, the data were imported into R Studio (**Fig. S5**), and each survey question 1-8 was treated as a continuous variable, and the respondents' characteristics, such as specialty, years of experience, and percentage of mobility-impaired patients, were included as categorical variables. A series of three-way analyses of variance ANOVA tests were performed for each survey question to assess their main effects and potential interactions between the categorical variables. For questions where significant differences were found, post-hoc analyses were conducted to identify specific differences between groups. This was done using Tukey's HSD test, which allowed for pairwise comparisons to pinpoint which specific groups differed from each other. All tests were performed using a significance level of 0.05, which indicates which variables significantly influence the respondents' opinions on the functionality and accessibility of current medical examination tables.

End Matter

Author Contributions and Notes

A.J. researched, selected, and 3D modeled high-low, scissor lift, and swivel mechanisms, S.G. researched, selected, and 3D modeled reclining mechanism and chair body parts, A.C. researched and selected materials, conducted price estimation, distributed and analyzed surveys, S.G. and A.C. created survey questions, S.G., A.J., and A.C. wrote the paper.

The authors declare no conflict of interest.

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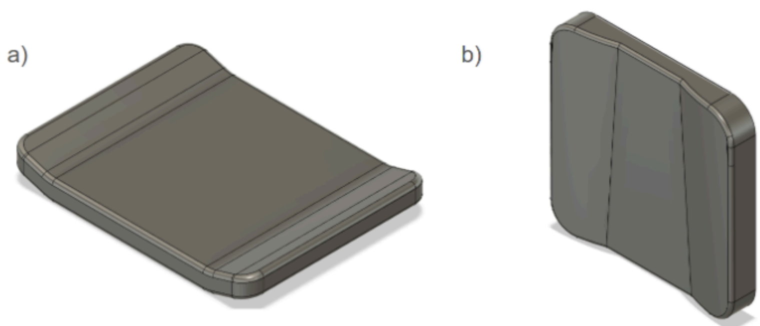
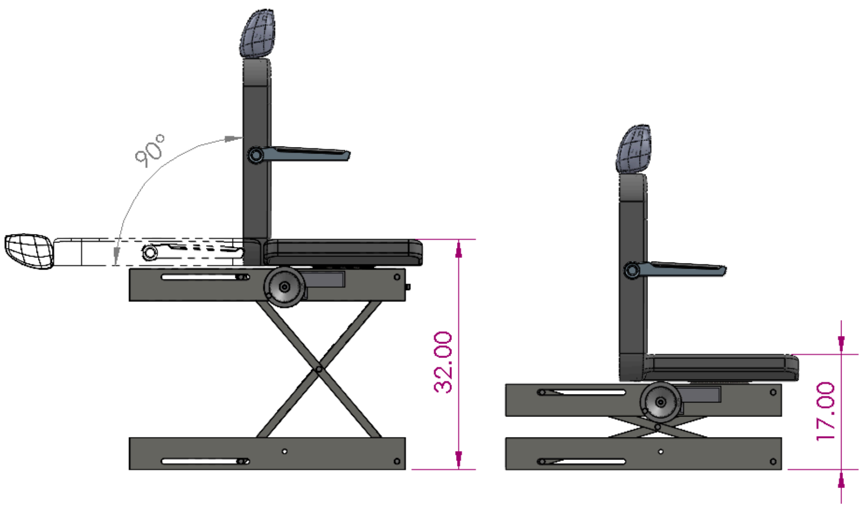
Supplementary Figures

Supplementary Figure 1: *Examination Chair Designed by Previous Capstone Group*



Supplementary Figure 2: *3D Models of the (a) Chair Seat and (b) Chair Back Inspired by the Previous Groups Work.*



Supplementary Figure 3: *Assembly of the Redesigned Exam Table Showing Range of Motion for Height Adjustability (Inches) and Reclining (Degrees).*

Upholstery: Polyvinyl Chloride (PVC)

Carolyn Fabrics (Highpoint, NC): +1 (336) 887-3101

- Spear millennium = 1 yard x 54 inches = $27.25 /yard

  1 yard = 36 in

  36 in x 54 in = 1944 in^2

  Yards needed = 2123.988 / 1944 in^2 = 1.09258642 yards

  1.09258642 yards x $27.25 = **$29.77**

Padding: EVA Foam

Worldwide Foam A Jacob & Thompsons Company (Elkhart, Indiana, Manufacturer): +1 (574) 968-8268

- 2lb EVA, 4 x 48 x 96, charcoal, 2 stage - $206.70 per sheet

  4 in x 48 in x 96 in = 18432 in^3

  4247.976 in^3 / 18432 in^3 = 0.2304674479 sheet

  0.2304674479 sheet x $206.70 = $47.63 + 150 handling fee = **$197.63**

Framework: 304 Austenitic Stainless Steel

North American Stainless (Wrightsville, Pennsylvania): +1 (502) 347-6000

- Surcharge = $79.44 + Base charge = $59.84 = goes on top of the per pound price
- 14 gauge = $1.3928/lbs (This is a rough guesstimate)

  1 lb = 0.453592 kg = $1.3928

  1 kg = $1.3928 x 0.453592 kg = $0.6317629376

  621.66 kg = $0.6317629376 x 621.66 kg = $392.74 + $79.44 + $59.84 = **$532.02**

Supplementary Figure 4: *Material Cost Calculations for the Chair*

```
# Set working directory
setwd("C:/Users/afsar/OneDrive/Documents")
list.files()

# Load libraries
library(ggplot2)
library(likert)
library(readxl)
library(tidyverse)
library(tidyr)
library(dplyr)
library(car)
library(emmeans)

# Read in data
dat <- read_excel("Statistical Analysis.xlsx")

# Extract relevant columns
Sp <- dat$Specialty
Ye <- dat$Yearsofexperience
Mi <- dat$PercentageofMobilityImpairements
Q1 <- dat$Q1
Q2 <- dat$Q2
Q3 <- dat$Q3
Q4 <- dat$Q4
Q5 <- dat$Q5
Q6 <- dat$Q6
Q7 <- dat$Q7
Q8 <- dat$Q8

# Example: ANOVA and post hoc for Q1
df_Q1 <- data.frame(Scale = Q1, Specialty = Sp, Ye = Ye, Mi = Mi)
Q1_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q1)
summary(Q1_aov)

# Repeat for Q2
df_Q2 <- data.frame(Scale = Q2, Specialty = Sp, Ye = Ye, Mi = Mi)
Q2_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q2)
summary(Q2_aov)
Q2_Ph <- TukeyHSD(Q2_aov, "Ye")
print(Q2_Ph)

# Repeat for Q3
df_Q3 <- data.frame(Scale = Q3, Specialty = Sp, Ye = Ye, Mi = Mi)
```

```
Q3_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q3)
summary(Q3_aov)

# Q4
df_Q4 <- data.frame(Scale = Q4, Specialty = Sp, Ye = Ye, Mi = Mi)
Q4_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q4)
summary(Q4_aov)

# Q5 with interaction post hoc
df_Q5 <- data.frame(Scale = Q5, Specialty = Sp, Ye = Ye, Mi = Mi)
Q5_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q5)
summary(Q5_aov)
df_Q5$Specialty_Mi <- interaction(df_Q5$Specialty, df_Q5$Mi)
Q5_interaction_aov <- aov(Scale ~ Specialty_Mi, data = df_Q5)
Q5_posthoc <- TukeyHSD(Q5_interaction_aov)
print(Q5_posthoc)

# Q6
df_Q6 <- data.frame(Scale = Q6, Specialty = Sp, Ye = Ye, Mi = Mi)
Q6_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q6)
summary(Q6_aov)

# Q7
df_Q7 <- data.frame(Scale = Q7, Specialty = Sp, Ye = Ye, Mi = Mi)
Q7_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q7)
summary(Q7_aov)

# Q8
df_Q8 <- data.frame(Scale = Q8, Specialty = Sp, Ye = Ye, Mi = Mi)
Q8_aov <- aov(Scale ~ Specialty * Ye * Mi, data = df_Q8)
summary(Q8_aov)
```

Supplementary Figure 5*: R Code Used for Statistical Analyses*