

Article

Data-Driven Design Solution of a Mismatch Problem between the Specifications of the Multi-Function Console in a Jangbogo Class Submarine and the Anthropometric Dimensions of South Koreans Users

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Abstract: The naval multi-function console provides various types of information to the operator. It is equipment that is key for submarine navigation, and fatal human errors can occur due to the mismatch between the console specifications and the operator's body size. This study proposes a method for deriving console specifications suitable for the body size of Korean users. The seat height, seat width, seat depth, upper edge of backrest, and worktable height were selected as the target design variables. Using six anthropometric dimensions, a mismatch equation for each target design variable was developed. Anthropometric measures of 2027 Korean males were obtained, and the optimal specifications of the console were derived via an algorithmic approach. As a result, the match rate, considering all the target design variables, was improved from 2.57% to 76.96%. In previous studies and standards, the optimal console specifications were suggested based on the anthropometric data of a specific percentile of users, and it was impossible to quantitatively confirm the suitability of the console design for the target users. However, the method used in this study calculated the match rate using the mismatch equation devised for comfortable use of the console and a large amount of anthropometric data that represented the user population, and therefore the improvement effect of the recommended specification can be directly identified when compared to the current specifications. Moreover, the methodology and results of this study could be used for deciding the specifications of multi-function consoles in several fields, including nuclear power plants or disaster situation rooms.

Keywords: multi-function console; data-driven design; mismatch equation; anthropometric measures; algorithmic approach; optimal design

1. Introduction

The naval multi-function console is part of the computer system of a battleship and it is designed for communication between the user and the computer. The console is connected to various sensors in the ship, it displays a variety of information, and the user is able to control the different types of information.

Although the crew members of South Korean Navy ships perform a variety of tasks depending on their position, most of the crew who are in the combat information and engine control rooms work in front of the console for more than 8 h on a daily basis. Console operators handle various types of information displayed on the console in a very concentrated state for a long period of time. Considering

the working characteristics of the console operators, they could be affected by various musculoskeletal disorders such as turtle neck syndrome and carpal tunnel syndrome, as well as chronic diseases such as low back pain and neck pain, if the height of the worktable or seat is inappropriate for the user's body size [1]. In addition, the ongoing physical burden on the console operators could probably lead to unintended operational errors, thus, reducing the mission efficiency and dispersing the focus on console operations [2].

Anthropometry means measurements of the human body. It is derived from the Greek words *anthropos* (man) and *metros* (measure) [3], and is needed in the design of machines, tools, and work environments in order to improve well-being, health, comfort, and safety [4]. The anthropometric data widely influence furniture design, and thus workplace design since the matching of body dimensions and furniture dimensions is vital to promote proper body posture for the user. An absence of anthropometry consideration would, in most cases, result in uncomfortable design for the targeted users and worse, unsafe, and unhealthy conditions. Therefore, to make the workplace comfortable for a person it should be designed based on an individual user's anthropometric dimensions [5,6]. Because of the importance of anthropometry, many previous studies have applied anthropometric methodologies to the design of the workplace [7–11].

Considering the improper posture of the console operator and the resulting decrease in concentration, which may significantly impact the ability to conduct military operations, continuous efforts to find the right specifications for the console operator's body size are necessary. If human factors and ergonomics (HF&E) approaches are not considered in the multi-function console design, musculoskeletal disease and human errors are more likely to occur [12], and thus several studies have emphasized HF&E's importance in suggesting design guidelines for consoles [13–15]. ABS (2013), MIL-STD-1472G (2013), and NUREG-0700 (2003) issued in the United States, are widely used as standards to provide guidelines for maritime system design, military equipment design, and nuclear power plant facility design, respectively. However, these standards mainly focus on providing minimum requirements rather than optimal design parameters when HF&E departments have associated with designers and engineers. In addition, the suggested criteria have been set based on the anthropometric data of only U.S. citizens [12]. Moreover, the basis and procedure for the optimal specifications recommended by these standards are unclear, and it is difficult to clearly confirm the improvement effect of the proposed optimal specifications as compared with the existing specifications.

The Korean Navy has solely focused on software improvements for operational performance of the console, and little attention has been given to hardware improvements to create a comfortable and secure console operating environment for users. Additionally, in Korea, the research on the development of military products that reflect the characteristics of the user's body has been focused on combat support systems such as military winter clothes, combat suits, and boots, and there is a relative lack of research on the ergonomic design of weapon systems such as the multi-function console. In the case of a combat support system, it is possible to improve a part of the product or to change the product within a short period of time when it is introduced and used in the military. However, the application of new design methods in a weapon system requires a longer period of time for development, and much more attention should be paid to a user-centered environment than that of a combat support system, because such design should be used for more than 20 years.

In this study, the console operating environment of the Jangbogo class submarine is presented as an example of the problems that may occur in terms of ergonomics when the specifications of the console are inappropriate for the user's body size. The seat height of the Jangbogo class submarine can be adjusted vertically, but the lowest height is measured to be 475 mm; seat width, seat depth, upper edge of backrest, and worktable height of the Jangbogo class submarine are measured to be 490, 482, 510, 817 mm, respectively.

2. Methods

Figure 1 shows the procedure for evaluating and improving the specifications of the submarine's multi-function console.

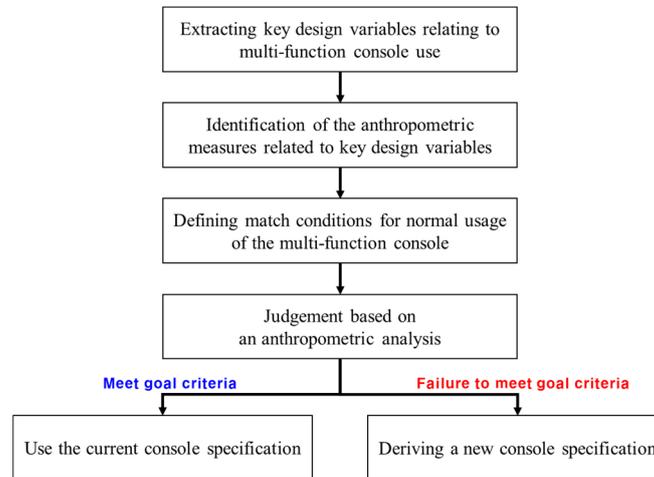


Figure 1. Procedure for design of submarine multi-function console using the anthropometric methodology.

First, the key design variables for multi-function console were extracted, and the detailed specifications of the current multi-function console were measured. Secondly, considering the context of the use of the console, anthropometric measurements related to the key design variables were identified. Third, the match conditions that guarantee a normal operation were also reviewed. Fourth, to judge the appropriateness of the current multi-function console specifications, the anthropometric dimensions were collected in consideration of the target population. Finally, after setting 70% of the match rate as the goal criteria, the suitability of the current multi-function console specifications was evaluated using a mismatch equation. In this study, an algorithmic approach was used to derive the optimal console specification, given that the match rate of the current multi-function console specifications did not reach the goal criterion.

2.1. Key Design Parameters for Naval Multi-Function Consoles

The multi-function consoles of Jangbogo class submarines have four consoles placed side-by-side, as shown in the first diagram in Figure 2. The four consoles are 2740 mm wide and 1300 mm high. The second diagram in Figure 2 is presented without the backrest to facilitate comprehension of the various design variables related to the seat. The third diagram in Figure 2 shows a lateral view of the console operator, also illustrating the specifications for different design variables.

First, the seat height (SH) of the seat refers to the vertical length from the floor to the highest portion of the seat pan. Previous studies related to the sitting posture at the work environment or to ergonomic design of student furniture have shown that the design of the SH is the utmost important factor. This means that determining the SH is the most important measure for solving a mismatch problem [16,17]. If the seat is too high, both feet are off the ground and high pressure is applied to the skin tissue behind the knee [18–20]. If the SH is too low, the seat pan does not support the thighs, and this can result in a large burden on the hips and an abnormally bent waist when sitting [21,22]. The current seat of the Jangbogo class submarine is designed to be adjustable for height. However, considering the fact that three or more console operators operate the console alternately in one day and a situation where the military is running an emergency training, there are instances when the operator has to switch quickly with the main console operator. Therefore, calculating the optimum height of the seat to return to the basic height would be very beneficial and effective in operating the console in terms of context of use.

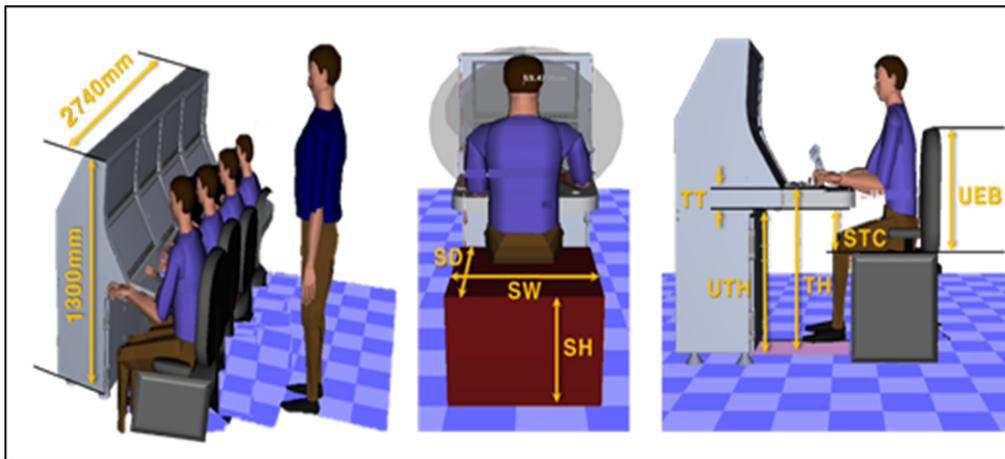


Figure 2. Submarine naval multi-function console design dimensions. Seat height (SH), vertical distance from the floor to the highest area of the seat pan; seat width (SW), horizontal distance from the left to the right side of the widest part of the seat pan; seat depth (SD), horizontal distance from the front to the rear of the longest part of the seat pan; upper edge height of backrest (UEB), vertical distance from the seat pan surface to the upper edge of the backrest (UEB); worktable height (TH), vertical distance from the floor to the worktable surface; underneath worktable height (UTH), vertical distance from the floor to the lowest point below the worktable; worktable thickness (TT), thickness of the worktable hardboard; and seat to table clearance (STC), vertical distance from the seat pan surface to underneath the worktable.

The seat width (SW) of the seat is the width from the left to the right side of the widest part of the seat pan. If the SW is too narrow, the sitting position may deviate from either side of the seat, and thus the width of the seat should be designed to be wider than the width of the user's hip [23–27]. Moreover, the upper limit of the SW needs to be considered, given that the seats are designed in a confined space and four console operators must sit side-by-side. In such context, Gouvali and Boudolos [28] argued that it is necessary to take into account an efficient utilization of the interior space in the submarine and to carefully derive the SW.

The seat depth (SD) is the length from the front to the back of the longest part of the seat pan. If the SD is too long, the backrest cannot support the back and waist properly, and the pressure between the front of the seat and the popliteal can increase, causing severe pain [20]. On the contrary, if the SD is too short, the pressure caused by the user's weight may not be evenly distributed through the user's hip and thigh, and the pressure may concentrate on a specific part of the body.

The upper edge height of backrest (UEB) means the vertical distance from the seat pan to the upper edge of the backrest. If the UEB is higher than the scapula, it may interfere with the free movement of the arms and torso [27,29]. Especially for console operators who work for more than 8 h per day, the above-mentioned situation can disable very basic activities such as stretching. However, if the UEB is too low, the back is not supported properly and this can induce excessive extension on the upper part of the back, which can lead to serious back injury.

The worktable height (TH) refers to vertical distance from the floor surface to the console platform surface. If the TH is too high, a console operator who frequently manipulates the keyboard and track ball installed on the worktable can suffer from excessive flexion and abduction of the shoulder and upper arm. In severe cases, this can lead to asymmetric spinal disorders. If the console TH is too low, the upper body is constantly bent forward and this can lead to kyphotic spinal posture [30].

The underneath worktable height (UTH) represents the vertical height from the floor to the lowest point of the worktable and the worktable thickness (TT) refers to the vertical distance from top to the bottom of the worktable.

The seat to worktable clearance (STC) represents the space between the seat and the worktable as the vertical distance from the extension of the seat pan surface to the bottom of the worktable.

This design variable is determined by the interrelationship between the seat and the worktable height. A too large STC implies that the seat is too low, or the worktable is too high. In such a case, discomfort can be induced in the shoulder and upper arm of the console operator, hindering normal shoulder movement. In contrast, if the STC is too narrow, sitting on the seat is not possible as the thigh can not enter between the seat and the worktable.

As the thickness of the worktable is fixed at 100 mm, there was no need for calculating the console UTH separately from the console TH. The STC between the seat and the worktable is also determined naturally when the SH and the TH are derived. The UTH, TT, and STC were measured to be 717, 100, and 142 mm, respectively.

Therefore, the SH, SW, SD, UEB, and TH were selected to be the final key design variables.

2.2. Anthropometric Criteria for Designing Naval Multi-Function Console in a Submarine

The age of the South Korean submarine crew ranges from 20 to 50 years, and they are only men. To consider the age of submariners, the seventh Korean anthropometric dataset for the age groups of 20–29, 30–39, 40–49, and 50–59 years were extracted from the survey made by SizeKorea in 2015. Six anthropometric measurements related to the target design variables of console operations were selected out of 133 anthropometric dimensions, as shown in Figure 3, which included: sitting thigh thickness (STT), popliteal height (PH), hip height (PH), hip width (HW), horizontal length between hips and ham (BPL), sitting shoulder height (SSH), and sitting elbow height (SEH).

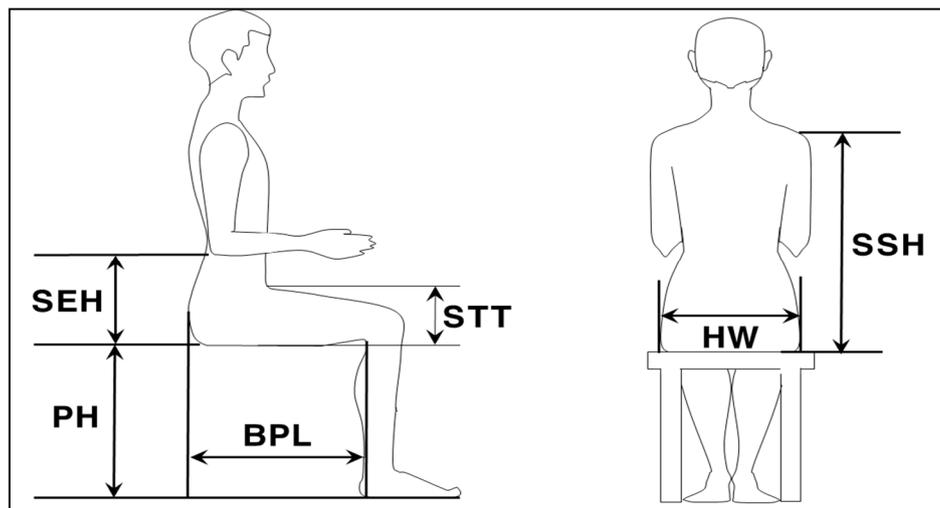


Figure 3. Anthropometric measures used in this study. Popliteal height (PH), vertical distance from the floor to the popliteal; hip width (HW), horizontal distance between the upper outer edges of the iliac crest bones of the pelvis; buttock to popliteal length (BPL), horizontal distance from the back of the buttocks to the popliteal; sitting thigh thickness (STT), vertical distance from the sitting surface to the superior thigh; sitting shoulder height (SSH), vertical distance from the sitting surface to the acromion; and sitting elbow height (SEH), vertical distance from the sitting surface to the underside of the elbow.

Descriptive statistical data of these six anthropometric measures for 2027 Korean males are presented in Table 1. They were used as the variables in the mismatch equation of this study.

Table 1. Anthropometric measures of Korean males between ages 20 and 50.

Anthropometric Measures	Mean (n = 2027)	SD	Min	Max	Percentiles		
					5	50	95
Popliteal height (mm)	428.01	20.5	353	523	395	428	463
Hip width (mm)	355.26	23.5	287	475	320	354	394
Buttock to popliteal length (mm)	490.46	22.9	420	592	454	490	530
Sitting thigh thickness (mm)	151.20	14.3	108	280	130	151	175
Sitting shoulder height (mm)	607.39	25.9	522	702	565	607	650
Sitting elbow height (mm)	268.79	25.1	195	364	227	270	309

2.3. Mismatch Equation for Naval Multi-Function Console in a Submarine

On the basis of the anthropometric measurements of the South Korean male, the mismatch equations used for specification of the key design variables in the submarine multi-function console define the maximum and minimum limits of those specifications.

All variables used in the mismatch equation were calculated in millimeter units.

First, the anthropometric dimensions for determining the SH was taken as the PH considering the sitting posture of the console operator as expressed in Equation (1). The shoe sole thickness (ST) was selected as the environmental variable.

$$(PH + ST) \times \text{Cos}30^\circ \leq SH \leq (PH + ST) \times \text{Cos}5^\circ \tag{1}$$

Equation (1) is based on constraints presented in Afzan, Hadi [31] and others [2,16,28,31–33], and this implies that the console operator should be able to extend at least 5° to 30° below their knees to feel comfortable when sitting in the seat. If the console operator sits at a right angle or at a smaller angle with the floor, fatigue can occur below the knee because of contraction of the tibial anterior muscle, and the excessive pressure can cause pain underneath the thigh if the knee is extended beyond 30°. The soles of submariners’ shoes are designed to prevent onboard noise and shock and they are measured to be 40 mm thick. Equation (1) used this measure for the calculation.

The anthropometric variable used to determine SW was selected based on the body part in contact with the seat and the environment inside the submarine. As four consoles are arranged side-by-side, as indicated in Equation (2), HW and STT are adopted. The thickness of various control devices that are attached to the side of the seat pan, called manipulator thickness (MT), and the winter clothes thickness (WT) of console operators are used as environment variables.

$$HW < SW \leq 685 - [STT + MT + (WT \times 2)] \tag{2}$$

Equation (2) is based on the equations discussed by Castellucci and Arezes [16] and other research works [16,31,33], but these studies did not suggest an upper limit for the SW. In previous studies that observed settings in offices and schools, there usually was a huge clearance between seats, and the clearances did not cause excessive inconveniences or problems. A study by van Niekerk and Louw [34] and others even suggests that the SW should be designed from 1.1 times to 1.3 times the HW for the user’s comfort and effective internal space utilization [28,32,34]. This study proposes an upper limit for SW considering the limited amount of space in a submarine setting, which requires it to be utilized in a very efficient manner. Figure 4 illustrates the deployment of four multi-functional consoles in Jangbogo class submarines.

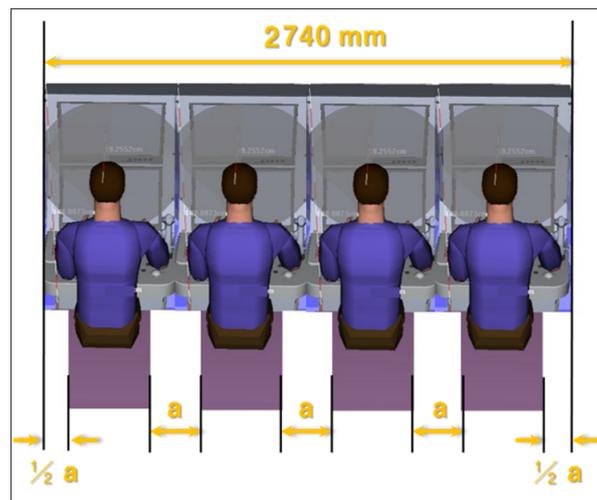


Figure 4. Deployment status of four submarine naval multi-function consoles.

In submarines, the consoles are arranged side-by-side to facilitate sharing of information among the four console operators. In the case of Jangbogo class submarines, only 2740 mm of horizontal space can be designed for all the consoles. If the seats are placed in the center of each console and if the distance between seats is represented by the character “a”, the width of “a” should be at least wider than the thickness of the user’s thigh considering the height of the seat because “a” should be designed to at least allow the console operators to enter and exit at “a”. The fact that various control devices are installed on the side of the seat pan and the instance where the submariners are required to quickly return to the seat from working outside of the submarine to perform their tasks without taking off their thick winter clothes must also be taken into consideration.

Therefore, in this study, the thickness of the control device was fixed to be 20 mm and WT was fixed to be 10 mm resulting in a total thickness of 40 mm with the expression $MT + (WT \times 2)$.

Considering the sitting posture with user’s back fully in contact with the backrest, the SD is determined using the BPL as shown in Equation (3) below.

$$0.80 \times BPL \leq SD \leq 0.95 \times BPL \quad (3)$$

Equation (3) was determined referencing to the equations used by Cotton and O’Connell [35] and others [2,16,31,33,35–43]. In particular, the coefficients presented in Equation (3) were calculated through various clinical trials in previous studies, and they were derived considering appropriate levels of comfortable knee extension and flexion when sitting with the hips and waist resting on the backrest.

As a parameter used for determining UEB, SSH was selected as shown in Equation (4) considering that the human body is in direct contact with backrest.

$$0.60 \times SSH \leq UEB \leq 0.80 \times SSH \quad (4)$$

Equation (4) was derived based on the findings of Agha [2] and other similar studies [2,31,32]. Each one of the coefficients, as those in Equation (3), was determined through a number of clinical trials. NUREG-0700 [15] recommends that the back of the seat should be able to support the lumbosacral region, which is the back curvature of the seat. Bendak and Al-Saleh [33] and Castellucci and Arezes [16] suggested only the upper limit of the UEB, stating that the UEB does not limit the basic upper body movement as long as the UEB is lower than the height of the user’s subscapula. However, as emphasized in NUREG-0700 [15], if the UEB is low enough to fail to support the lumbar regions, it cannot properly support the back and waist, leading to their excessive extension. Therefore, the lower limit of the UEB must be also considered.

Equation (5) for the STC was devised based on the concept that the console operator's thigh should be able to fit under the worktable.

$$STT + 20 + (2 \times WT) \leq STC \quad (5)$$

The existing research recommended 20 mm for the sitting thigh thickness [28,29,36], but we added 10 mm considering the WT.

TH is determined by SH, thickness of the worktable, and STC. Therefore, this can be expressed in Equation (6) as follows:

$$TH = SH + TT + STC \quad (6)$$

Combining Equations (1), (5), and (6), the lower and upper limits of TH can be determined as expressed in Equation (7). In Equation (7), STT, SEH, PH, and SSH were selected as the anthropometric variables, whereas TT, WT, and ST were selected as environmental variables.

$$\begin{aligned} \text{Max}[STT + 20 + (2 \times WT) + TT, SEH] + [(PH + ST) \times \text{Cos}30^\circ] &\leq TH \\ &\leq (0.8517 \times SEH) + (0.1483 \times SSH) + [(PH + ST) \times \text{Cos}5^\circ] \end{aligned} \quad (7)$$

In Equation (7), the lower limit of the TH was chosen to be the higher value in between STC and SEH. This means that, in the sitting state, the height from the floor to the console operator's thigh should be lower than the UTH, and the elbow should be able to reach the worktable comfortably. If TH is lower than SEH, it would be very difficult to rest the elbows on the worktable without bending down, and manipulation of the keyboard and track ball would force the operator to bend forward. Considering the context of a console operator who heavily uses keyboards and track balls, the tension in the shoulder and back muscles can only increase if the elbows are not comfortably sitting on the worktable. The upper limit of the TH was derived by multiplying SEH and SSH by specific coefficients and then adding the calculated numbers to the upper limit of SH. The coefficients multiplied by SEH and SSH are given by the research of Parcells and Stommel [36] and Chaffin [44], who mathematically calculated the range of motion of the shoulder's flexion and abduction when working on a worktable and resting the arms on the worktable. If the height of the worktable is greater than the upper limit suggested by Equation (7), the shoulders can be excessively elevated upwards, or the arms are opened too widely to the sides when the elbows are raised on the worktable. This can cause increased fatigue and lead to musculoskeletal disorders of the shoulder and arm after a period of repeated tasks with the given environment.

2.4. Data Treatment

The minimum and maximum acceptable limits were calculated using the mismatch equation with specifications of six anthropometric measures. The equation was substituted with the anthropometric measurements of 2027 Korean males in the age groups of 20 to 29, 30 to 39, 40 to 49, and 50 to 59 years to verify whether the current multi-function console is suitable for the Korean body sizes. Each design specification of the current console that mismatched the Korean anthropometric dimension was determined, and the reasons behind the mismatch were analyzed. This study used Excel 2016 and SPSS25.0 to analyze the data. In addition, the greedy algorithm approach, which was utilized by Lee and Kim [45] to find the optimal height system for the chairs and desks of Korean students, was applied to derive the optimal specifications for the target design variables, and R programming was used to implement the greedy algorithm to calculate the optimal specifications of the console. The greedy algorithm approach is simple and primitive as it finds the maximum match rate of a specification by substituting the anthropometric dimension of each user in the mismatch equation and incrementing it by 1 mm sequentially for all possible specifications. Despite the simplicity of this algorithm, so far, it is essentially the best possible polynomial time approximation algorithm for the maximum coverage problem [46].

3. Results

Figure 5 shows the mismatch rates of the key design variables of the current multi-function console.

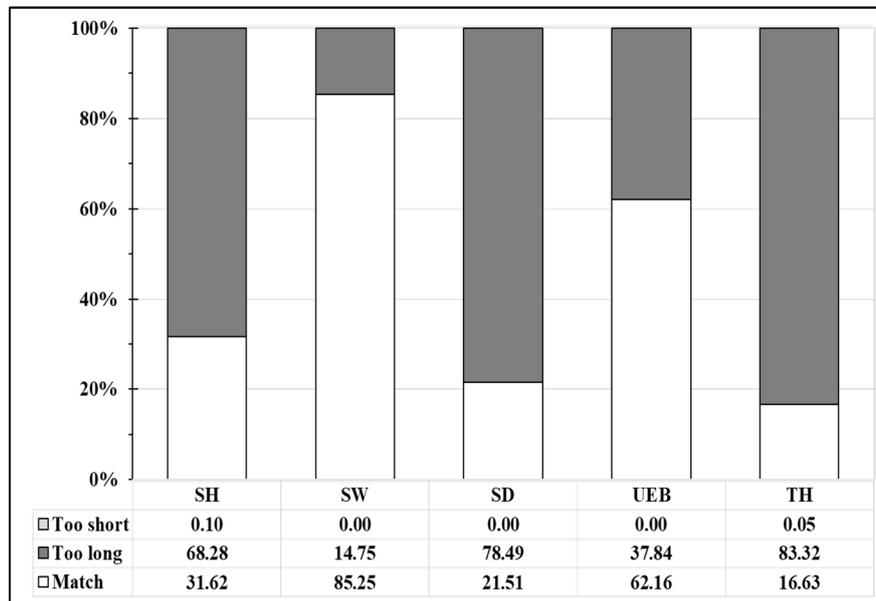


Figure 5. Mismatch rate of design specifications of the present submarine console.

First, the match rate of the current SH of Korean male body size was found to be 31.62%. In particular, the current SH was found to be higher than the body size of most men (68.28% of total), who were determined to be mismatched for the current size of SH. This means that the current SH is excessively high considering the user’s PH. In this case, the majority of men were incapable of naturally touching the floor with their feet while resting their back on the backrest.

Secondly, the match rate of the current SW to the Korean male body size was 85.25%, and SW was considered wider than the HW of all men. It was found that 14.75% of men were mismatched for the current SW, which is wider than their anthropometric dimensions. The upper limit of the SW proposed in Equation (2) was defined only to set an effective utilization of the limited space in a submarine and, given that 14.75% of the Korean anthropometric dimensions were determined to be mismatched, the current SW do not present any problem for sitting purposes.

Third, the match rate of the current SD turned out to be 21.51%. In particular, the current SD was identified as inadequate for 78.49% of men as it was too long for their anthropometric dimensions. This indicated that the current SD is relatively longer than the BPL. Therefore, these men cannot sit with their backs in contact with the backrest or cannot bend their knees while sitting down. They are very likely to sit very unnaturally or uncomfortably, for instance sitting on the end of the seat while operating the console.

Fourth, the match rate of the current UEB for the Korean male size was 62.16%, and it showed the highest match rate of all the key design variables. However, 37.84% of men were identified to be mismatched for the current backrest height, which is higher than their scapula height. By limiting their upper body rotation and basic movements, the current backrest height can stiffen the user when operating the console for a long time.

4. Discussion

4.1. Analysis of Mismatch Conditions

This section examines whether the specifications of the multi-function consoles currently installed in Jangbogo class submarines meet the specifications recommended in previous studies or the

standards. The result of the mismatch equation is also carefully analyzed and organized for each key design variable.

First, the current SH was found to be too high for the body size of the majority of Korean males. ABS [13] and MIL-STD-1472G [14] recommend that the SH is between 380 to 540 mm considering the user's PH. Although the current SH complies with the range suggested by the above-mentioned standard, considering the ST (40 mm), the current SH should be lowered as the average PH of Korean males is 428.01 mm, and sitting with 475 mm of SH can cause discomfort to the users as their feet do not touch the floor.

Secondly, the match rate of the current SW was 85.25%, which was significantly higher than the match rate of the other target design variables. MIL-STD-1472G [14] and ISO9241-5 [47] recommended that the seat should be at least 460 mm wide to fit the person with the widest hip. The current SW was 490 mm, and thus it was confirmed to meet the recommended specification. In addition, considering the fact that the size of the widest HP of Korean male is 475 mm, the current SW is not expected to cause any difficulty to the sitting task of console operators. However, the current seat is too wide for 14.75% of men and the SW could be narrowed to more effectively utilize the limited space in the submarine. It would not be a big problem to make the SW slightly narrower than it is now.

Third, the current SD has a match of only 21.51% for the Korean male body size and it turned out to be the worst fit for most men. NUREG-0700 [15] and MIL-STD-1472G [14] recommended that the depth of the seat should be from 381 to 431.8 mm considering the body size with the shortest BPL. The current SD of the seats installed in Jangbogo class submarines is 482 mm, and thus it is much longer than what is recommended. Among the Korean male anthropometric dimensions used in this study, the dimension of the user with the shortest BPL is only 420 mm and the BPL of users in the fifth percentile is only 454 mm. Therefore, it would be very difficult for them to bend their knees comfortably while leaning back on their backrest and sitting with a correct posture on the seat. There is a need to improve the SD by reducing the depth.

Fourth, the match rate of the current UEB was 62.16% and it is considered higher than the match rate of other key design variables. MIL-STD-1472G [14] recommended that the UEB should be from 480 to 580 mm so that users can support their torso well while they are sitting. The current UEB of the Jangbogo class submarine seat is 510 mm and it is considered to be in the recommended range. However, 37.84% of users have a high UEB, and hence they are hindered from making basic upper body movements. In addition, considering the unique usage context of the submarine console, where there is an administrator who monitors the console information from behind the seat, it is necessary to lower the UEB of the current seat.

Finally, the match rate of the current TH to the Korean male body size was only 16.63%. The TH is closely related to the SH, STT, and PH [47]. MIL-STD-1472G [14] and ABS [13] recommended that the TH should be in the range 740–790 mm and 650–810 mm, respectively. However, the current TH in the Jangbogo class submarine is 817 mm, which is greater than the height recommended by the standard. When the user works on a worktable that is higher than his or her body size, the manipulation of the keyboard and track ball tasks for a long period of time can be restricted because the comfortable operation of the shoulder joint and upper arm is not guaranteed.

Meanwhile, the STC is naturally determined by the SH and the TH. ISO9241-5 [47] suggested that the STC should be designed in consideration of human body size with the thickest thigh, and NUREG-0700 [15] recommended the STC to be at least 190.5 mm. The STC of the Jangbogo class submarine is currently 242 mm, which satisfies the recommended specification of NUREG-0700 [15]. However, considering that the thickest STT measurement from SizeKorea is 280 mm, the vertical adjustable range of the seat should be lowered further downwards.

The ISUS 83 combat command system and multi-function console of the Jangbogo class submarine were acquired from Germany in 1992, and these were developed in the early 1980s to enhance the performance of the German Navy's 206 submarine. Therefore, it is very likely that these consoles were built reflecting the dimensions of the German human body size measured in the 1980s. The German

adult male had an average height of 180.5 cm in 1980 [48], whereas the Korean average height was only 172.9 cm in 2015. Therefore, it is natural that the size of the console designed for the German body size at the time mismatched the Korean male's anthropometric dimensions. Therefore, to obtain the optimal design specifications for the console matching the Korean anthropometric dimensions, the specification for each key design variable is proposed in Section 4.2, based on the results of the above analysis.

4.2. Recommendations for the Specifications of Submarine Naval Multi-Function Consoles Considering South Korean Body Size

One of the most commonly used methods in the development of standard systems, which was used in previous studies determining specifications of furniture for students, is the Ellipse methodology [17,49,50]. This method recommends an appropriate design range based on the fifth to 95th percentile dimensions of the collected anthropometric dimensions. For example, this method is implemented when determining the size of a hat; the head circumferences of the fifth and 95th percentile hat users are measured, and then, the size of the hat is determined within the range of the two.

In the case of the console, there are more anthropometric considerations to determine the specifications of each key design variable. To produce a single specification that can accommodate as many users as possible, it would be more appropriate to search for the optimal specification with the maximum coverage problem rather than the elliptic methodology.

To maximize match rate between each specification of the key design variables and anthropometric dimensions, the specifications listed in Table 2 were found to be the optimal.

Table 2. Recommended specifications for the South Korean submarine console.

Design Variable	SH	SW	SD	UEB	TH
Recommended Specification	431 mm	442 mm	429 mm	442 mm	738 mm

Among the recommended specifications presented in Table 2, SH, SD, and TH were within the recommend ranges in the previous standard, and UEB was approximately 38 mm lower than the existing standard. However, considering that the previous standards are from measurements in the United States and the fact that UEB is lower than the previous standard, while all the other design variables meet the recommended specification at the lower limit, it is inferred that the recommended specifications in Table 2 more practically reflect the Korean anthropometric dimensions for submarine consoles than the previous standards.

The existing standard recommends the SW to be wider than 460 mm, while the derived specification from the algorithmic approach was narrower by 18 mm. The widest hip width (475 mm) of Korean male adults cannot sit in the recommended SW but it is enough to fit the 95th percentile (394 mm). Considering the limited space inside the submarine, the seat specifications are considered to be appropriate. In addition, according to the recommendation in Table 2, the STC is 207 mm, which meets the minimum recommended standard proposed by NUREG-0700 [15]. Given that the seat can be adjusted vertically, when the SH is adjusted at a lower level, the console operators with the thickest thigh will be able to use the console.

Figure 6 shows a comparison between the match rate of the current console specification and that of the recommended specification.

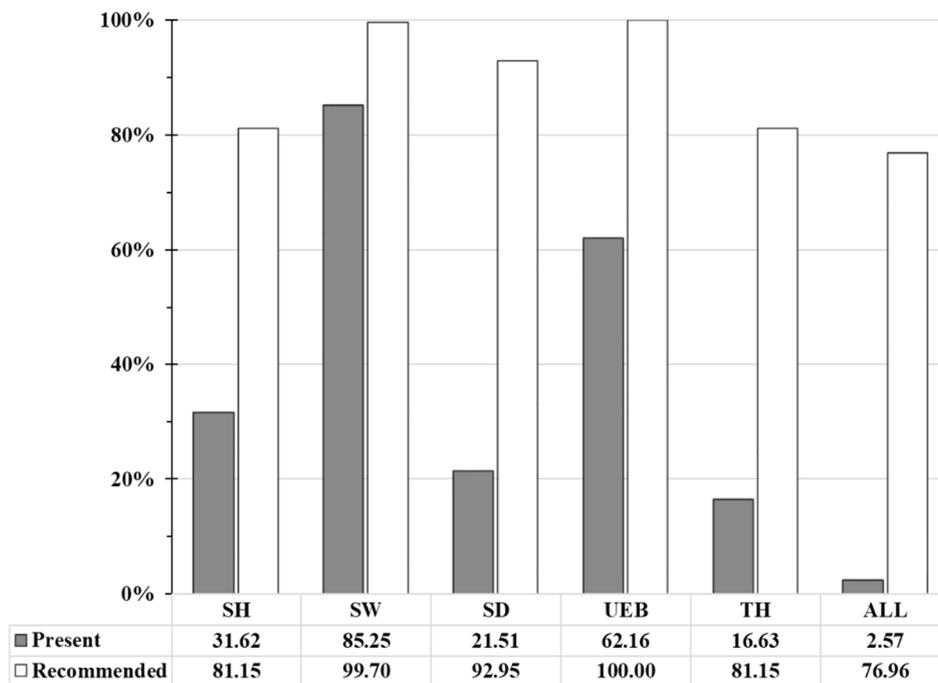


Figure 6. Comparison of match rate between the present and recommended specifications of the submarine console.

The match rates of the SH and TH are 81.15%, and it has been found that many more users can be accommodated than before. The SW, SD, and UEB are expected to fit 99.70%, 92.95%, and 100% of the Korean body sizes, respectively.

The rate of Korean males who have a suitable human body size for all five target design parameter specifications in the current console specification is only 2.57%, thus, on the one hand, 97.43% of users may have difficulties in using current console. On the other hand, it is expected that 76.96% of users have a suitable human body size for recommended console specification, and therefore many more users should be able to use the console comfortably as compared with the previous current console. Furthermore, considering the SH is adjustable, the number of the users who can comfortably use the console designed according to the recommended specifications is expected to be much higher.

In this study, human body size of only Korean males was used in calculating optimal design specifications of submarine console used by Korean submariners. However, if the anthropometric data for American or German users is applied with the methodology used in this study, it is expected that the optimal console specifications suitable for Americans or Germans could also be easily derived.

5. Conclusions

In this study, we derived the optimal design specifications for a multi-function console of Jangbogo class submarines that can accommodate, as much as possible, the anthropometric dimensions of Korean males.

To calculate the appropriate ranges for the key design variables, the working posture, the working environment, and the cooperation situation with other operational personnel were considered. The anthropometric dimensions of 2027 Korean male adults were substituted in the mismatch equation of each design variable to confirm the suitability of the Korean male body size for the current console.

All the key design variables, except the SW, were found to be inappropriate for the majority of Korean male’s body sizes. To solve these problems of mismatch, we derived the optimal console specification through an algorithmic approach. As a result of calculating the match rate, it was found that the match rate can be improved up from 2.57% to 76.96% if the console is designed with the specifications proposed in this study.

The mismatch equation and algorithmic approach used in this study could further be used as a guideline for the specification of various military consoles in Korea, and it could be used to design work environments in various fields that operate multi-function consoles such as nuclear power plants and disaster control centers.

However, the mismatch equation used in this study is based on the previous studies dealing with the optimization of school furniture for the students or children. Therefore, it is necessary to verify through further empirical experiments whether the proposed mismatch equation is also valid for the working environment of the multi-function console and to continuously improve the equation if needed. In addition, this study was limited to the search for the optimal specifications of design variables related to the height of submarine consoles. Thus, in future research, the optimal specifications of distance-related design variables, such as depth of worktable, horizontal distance between seats and worktables, and placement radius of the various control buttons on the console, should be explored based on the reach envelope of Korean users.

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