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INTEGRATING MODEL AND SMARTPHONE TECHNOLOGIES FOR COLD-WATER THERMOREGULATION ASSESSMENT

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This study investigates human thermal and physiological responses during water immersion. The task addressed relates to the current gap between sophisticated, expert-driven mathematical models of thermoregulation and the practical demand for accessible tools to assess thermal risks in open water.

To bridge the gap, this paper proposes a method based on the integration of a multicompartmental mathematical model of human thermoregulation with a mobile application. The results of the study confirm the method's effectiveness in predicting human physiological responses during water immersion. Model validation against experimental data demonstrated strong concordance, particularly in reproducing core temperature dynamics under cold-water exposure (Theil index ≈ 0; $t(9) = 2.16$, $p > 0.05$).

Modeling results indicate that moderate activity (300 W) in water at a temperature of 10°C leads to a decrease in internal temperature, whereas higher activity levels (600 W) are sufficient to maintain normal body temperature. Wetsuits play a critical role in preserving human temperature regime during cold-water immersion; without a wetsuit, passive immersion at 17°C results in hypothermia within 60 minutes ($T_{core} < 36$°C). Conversely, during high-intensity exercise (1100 W), wetsuits may increase thermal strain, with body temperature rising to 39.2°C over 60 minutes, while in the absence of protective clothing – $T_{core} = 38.1$°C.

The findings provide quantitative insights into the influence of water, immersion level, activity, and wetsuit on human thermal responses. The app that was developed could predict safety guidelines for aquatic sports and recreational activities

Keywords: model, physical activity in water, cold stress, extreme environment, health risk

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1. Introduction

Aquatic activities are becoming increasingly popular in sports, professional activities, and leisure, but exposure to water poses significant thermoregulatory risks. Because water has a much higher thermal conductivity and heat capacity than air, prolonged exposure to cold water can quickly deplete the body's defenses and cause hypothermia [1, 2]. In contrast, intensive swimming or exercising in water while wearing thermally insulating clothing (e.g., wetsuits) can reduce heat loss, increasing the risk of hyperthermia [3, 4].

A wide range of aquatic activities and occupations put people at risk of severe hypothermia. Open water swimmers, military personnel, and rescue workers spend extended periods of time in cold water. Environmental conditions are particularly dangerous, as open water competitions typically carry a risk of hypothermia [5, 6].

Real-life cases confirm the seriousness of these threats. During a 19.2 km open water swim in Western Australia, 26 of 35 swimmers who required medical attention were diagnosed with hypothermia, and some had to be hospitalized [7]. In response to such incidents, World Aquatics (formerly FINA – Fédération internationale de natation) introduced minimum water temperature thresholds and maximum swim time limits to reduce the risk of hypothermia during competition [8].

The risk to human thermoregulation is not limited to cold environmental conditions. During intense exercise in water, especially when wearing a wetsuit, heat can accumulate in the human body, increasing the risk of hyperthermia [3, 8]. In view of this, competition regulations increasingly set upper limits for water temperature, taking into account the potential risk of increased internal body temperature during prolonged, high-intensity swimming in a wetsuit [9].

Modern human health monitoring systems are mainly focused on response, rather than preventive assessment of thermoregulation risks [10]. Existing mathematical survival models used by expert communities (in particular, coast guards) make it possible to assess the consequences of cold water exposure but are not designed to provide recommendations in real time. These limitations determine the relevance

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of scientific research in this area since there is a need to integrate proven thermoregulation models with digital technologies to predict human physiological and thermal responses in water. This has important practical significance as it lays a foundation for designing hypothermia prevention systems, which could contribute to increasing safety in the aquatic environment. The implementation of such systems is of critical importance for rescue services, athletes, and other categories of persons engaged in activities in open water.

2. Literature review and problem statement

The rapid development of mobile applications and wearable devices has enabled continuous monitoring of human physiological status. These technologies provide real-time assessment of vital signs, including heart rate, blood pressure, and metabolic parameters [11, 12]. At the same time, mobile applications have been developed for the general public to increase situational awareness of water safety. For example, the web and mobile application "Surf Life Saving Australia's Beachsafe" provides beachgoers with up-to-date information about coastal conditions. In particular, this includes data on current weather, tides, waves, beach hazard ratings, patrolled swimming areas, and available infrastructure [13]. The advantage of such systems is that they significantly increase users' situational awareness, which helps them make more informed decisions about water activities. At the same time, an unresolved aspect is the lack of personalization: these technologies provide information about general conditions but are unable to predict human physiological responses, taking into account his/her condition, level of physical activity, and characteristics of protective clothing.

Continuing the evolution of monitoring technologies, experimental and commercial systems have been designed to detect risks associated with diving in real time. Prototypes of multisensory wearable devices continuously monitor heart rate, movement patterns and depth of immersion, automatically notifying of danger when preset thresholds are exceeded [14]. The "Rush" device additionally monitors breathing and blood oxygen saturation and also serves as an acoustic beacon to direct rescuers to swimmers in distress [15]. Among commercial platforms, WAVE's GUARDian system uses waterproof tags and headbands that activate vibrating alerts if a swimmer remains underwater for a set period of time [16]. Blueguard integrates AI-based video surveillance with biometric wristbands to detect early signs of drowning [17]. The advantage of such systems is their ability to automatically detect life-threatening situations in real time and provide immediate notification. However, they only work after a critical situation has occurred, as they focus on simple metrics rather than complex thermoregulatory models. This limits their ability to predict risks in advance.

In parallel with the development of wearable devices, research groups and government agencies are designing computational tools to estimate survival time in water. The US Coast Guard uses the Probability of Survival Decision Aid (PSDA) computer program. This program is based on a six-cylinder thermoregulatory model that makes it possible to predict survival time taking into account hypothermia. The model takes into consideration environmental parameters (water and air temperature, humidity and wind speed), anthropometric data, and characteristics of protective equipment [18]. The advantage of this model is its high scientific validity and ability to accurately predict survival time, which makes it an important tool for professional communities. However, its scope of application remains limited: the model is intended exclusively for use by specialists in search and rescue operations, and not for individual use.

The Canadian Defense Research and Development Center (DRDC) built the Cold Exposure Survival Model (CESM) to predict maximum survival time under cold stress. CESM is widely used in NATO search and rescue operations to plan the duration of search efforts taking into account the risk of hypothermia [19]. The advantage of CESM, like PSDA, is its reliability and validation for predicting critical states under cold stress conditions, which is the standard for expert planning. However, this tool also has limited availability as it is intended exclusively for expert communities and remains unavailable for individual use.

The UK National Immersion Incident Survey (UKNIIS) has compiled the world's largest database of around 1,600 incidents documented by the Coastguard (as of 2022) [20]. The UKNIIS data has been used to build survival prediction models and search and rescue planning. The value of the UKNIIS is to provide a unique, real-world dataset that is an invaluable source for retrospective analysis and validation of survival models. However, a direction for further research is to overcome the limitation of the lack of detailed physiological parameters for each case. This feature makes it impossible to construct and validate highly accurate personalized predictive models.

Analysis of existing solutions has revealed several local problems. First, publicly available information systems increase situational awareness but do not take into account individual physiological responses. Second, wearable emergency notification devices operate under a reactive mode, responding to an already occurring hazard rather than predicting it. Third, scientifically based thermoregulation models (PSDA, CESM) are powerful but complex and inaccessible to average users. Fourth, large incident datasets do not contain enough information to design personalized predictive tools.

The systematization of the identified limitations demonstrates the lack of a method that would combine proven mathematical thermoregulation models with available digital tools. Solving this problem will enable the transition from general recommendations and incident response to individual prevention of thermal risks to human health while in the water.

3. The aim and tasks of the study

The aim of this study is to devise a method for predicting human thermal and physiological responses during cold water immersion, which is based on the integration of a mathematical model of thermoregulation with a mobile application.

To achieve the goal, the following tasks were set:

– to prove the validity of the mathematical model of human thermoregulation by comparing the results of modeling with measurement data on volunteers;

– to design a client-server architecture that ensures the integration of the mathematical model with a mobile application;

– to develop a mobile application for predicting temperature risks taking into account environmental conditions, immersion level, intensity of physical activity, and characteristics of protective clothing;

– to assess the human thermal and physiological responses in water under different environmental conditions and physical activity, taking into account protective clothing.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of this study is the human thermal and physiological responses during immersion in water.

The hypothesis of the study assumes that the integration of a mathematical model of thermoregulation with a mobile application could provide the possibility of preventive assessment of temperature risks and prediction of the human thermophysiological state in water.

The study examines the human thermal and physiological responses without pathological deviations. It is assumed that a man does not have diseases that can affect thermoregulatory responses and does not take medications that change metabolic processes.

Environmental conditions and physical activity are constant during the forecasting period. The characteristics of protective clothing are average values without taking into account individual features of the cut, tightness of fit to the body, and zones of increased water permeability.

4. 2. Multicompartmental mathematical model of human heat exchange with water

The model of human heat exchange has a multicompartmental structure. The human body is fitted to 14 segments that have a multilayer structure, where each layer is a compartment: core, muscles, fat, and skin. The mathematical notation of heat generation in the body, heat transfer, and heat exchange of a man with the environment for the *ij*-compartment takes the following form [21–25]:

$$\begin{cases} c_{ij}m_{ij}\dfrac{dT_{ij}}{dt}=M_{ij}+a_{ij-1}\lambda_{ij-1}\left(T_{ij-1}-T_{ij}\right)-a_{ij}\lambda_{ij}\left(T_{ij}-T_{ij+1}\right)- \\ -\rho_b c_b w_{ij}\left(T_{ij}-T_b\right)-h_{ij}^{C}A_{ij}\left(T_{ij}-T_i^{a}\right)- \\ -h_{ij}^{R}A_{ij}\left(T_{ij}-T_i^{a}\right)-h_{ij}^{E}A_{ij}\left(P_{ij}-\dfrac{\varphi_i}{100\%}P_i^{a}\right)- \\ -h_{ij}^{w}A_{ij}\left(T_{ij}-T_i^{w}\right),\ i=\overline{1,N},\ j=\overline{1,K}, \\ V_b\rho_b c_b\dfrac{dT_b}{dt}=\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{K}w_{ij}\rho_b c_b T_{ij}-W_b\rho_b c_b T_b-Q^{RS}, \end{cases} \tag{1}$$

where c is the specific heat capacity, kcal/(kg · °C); m is the mass of tissues, kg; T is the compartment temperature, °C; T^a is the air temperature, °C; T^w is the water temperature, °C; t is the time, h; M is the metabolic rate, W; a is the compartment thickness, m; λ is the thermal conductivity coefficient of the tissue, W/(m · °C); ρ is the density, kg/m^3; w is the blood flow, l/h; A is the surface area of the human body, m^2; h^C is the convection heat transfer coefficient, W/(m^2 · °C); h^R is the radiation heat transfer coefficient, W/(m^2 · °C); h^E is the evaporation heat transfer coefficient, W/(m^2 · kPa); h^w is the convection and conduction heat transfer coefficient in water, W/(m^2 · °C); φ is the relative humidity, %; P is the saturated vapor pressure near the skin surface, kPa; P^a – saturated vapor pressure in the ambient air, kPa; V_b – blood volume in the large veins, l; W_b – cardiac output, l/h; Q^{RS} – respiratory heat loss, W; indices: i – body part number; j – compartment number; b – blood; N – number of body parts; K – number of compartments within one body part.

The heat transfer coefficient between a man and water is calculated from the following formula

$$h^w=\frac{\lambda^w\cdot \mathrm{Nu}}{d}, \tag{2}$$

where λ^w is the thermal conductivity of water, W/(m · °C); Nu is the Nusselt number, Nu ≥ 1; d is the diameter, m.

The Nusselt number is defined in [26]:

– free convection

$$\mathrm{Nu} = 0.54(\mathrm{Pr}\cdot \mathrm{Gr})^{1/4},$$

– forced convection

$$\mathrm{Nu} = 0.66\cdot \mathrm{Re}^{1/2}\cdot \mathrm{Pr}^{1/3},$$

where Re is the Reynolds number; Pr is the Prandtl number; Gr is the Grashof number.

The Reynolds number is determined from a formula in [26]

$$\mathrm{Re}=\frac{v\cdot d_{ij}}{\mu}, \tag{3}$$

where μ is the kinematic viscosity of water, m^2/s.

The Prandtl number is determined from a formula in [26]

$$\mathrm{Pr}=\frac{\mu}{D}, \tag{4}$$

where D is the thermal diffusivity of water, m^2/s.

The Grashof number is calculated from a formula in [26]

$$\mathrm{Gr}=\frac{\beta\cdot g\cdot (d)^3\cdot\left(\overline{T_{sk}}-T_{water}\right)}{(\mu)^2}, \tag{5}$$

where β^{water} is the temperature coefficient of volumetric expansion of water, K^{-1}; g is the acceleration of gravity, $g \approx 9.81$ m/s^2.

The dependence of heat transfer coefficients on human movements and the presence of water flow is given in [27]. In still water, in the absence of human movements, the heat transfer coefficient is 230 W/(m^2 · °C), at high flow velocity (0.5–0.75 m/s) or during swimming – 460 W/(m^2 · °C).

The influence of water velocity and temperature on heat transfer coefficients between a man and water was shown in [28]. Table 1 gives empirical formulas for heat transfer coefficients for free and forced convection in thermoneutral and cold water. The thermoneutral temperature of water is 35°C [29].

Table 1

Heat transfer coefficients in water [28]

Conditions	Free convection	Forced convection
Thermoneutral water	$h = 415.38\cdot \upsilon + 41.48$	$h = 272.94\cdot \upsilon^{0.5}$
Cold water	$h = 589.97\cdot \upsilon + 53.07$	$h = 497.13\cdot \upsilon^{0.65}$

Note: υ – water velocity relative to the human body, m/s.

A decrease in water temperature causes thermoregulatory responses in humans.

4. 3. Modeling human thermoregulatory responses in the aquatic environment

In cold water (below 35°C), human protective regulatory responses are developed: the vascular reaction of the skin, which helps retain heat in the human body, and the shivering of human skeletal muscles, which generates additional heat.

The speed of blood movement in human skin while in water takes the following form:

$$W_{sk} = W_{sk}^* - S_{br}\left(T_{br}^* - T_{br}\right) - S_{sk}\left(T_{sk}^* - T_{sk}\right), \quad (6)$$

if $T_{sk} \geq H_{sk}^w$ and $T_{br} \geq H_{br}^w$,

where W – blood flow, l/h; T – temperature, °C; S – sensitivity of the thermoregulation center, l/(h · °C); indices: * – initial value; *br* – brain; *sk* – skin.

Additional heat production during cold tone and involuntary contraction of skeletal muscles of the body is calculated from the following formula:

$$M^{sh} = A\left(\frac{155.5\left(T_{br}^* - T_{br}\right) + 47.0\left(T_{sk}^* - T_{sk}\right) - 1.57\left(T_{sk}^* - T_{sk}\right)^2}{\sqrt{\%BF}}\right), \quad (7)$$

if $T_{sk} \geq H_{sk}^{sh}$ and $T_{br} \geq H_{br}^{sh}$,

where M^{sh} – shivering, W; A – surface area, m^2; $\%BF$ – amount of subcutaneous fat as a percentage of the total body weight.

5. Results of modeling the thermophysiological responses in water

5. 1. Validating the mathematical model of human thermoregulation in water

The mathematical model was validated by comparing prediction results with the experimental data reported in [30]. 10 healthy volunteers – 6 men and 4 women – participated in that study. Mean values ± standard deviation: age 26 ± 6 years, height 1.70 ± 0.12 m, weight 73.4 ± 13.3 kg, and body mass index 24.9 ± 3.0 kg/m^2. Participants dressed in bathing suits, placed in a large tank, were immersed up to the middle of the chest in water with a temperature of 10°C. The ambient air temperature during measurements was maintained at 23°C. Gastrointestinal temperature was measured using a sensor capsule (swallowed 3–6 h before immersion) every 5 min during the 90-min exposure.

The mathematical model allows for an accurate reproduction of the experimental conditions [30]. The results of simulating the dynamics of internal body temperature during immersion in water at 10°C for 90 min are in good agreement with data measured in humans (Fig. 1).

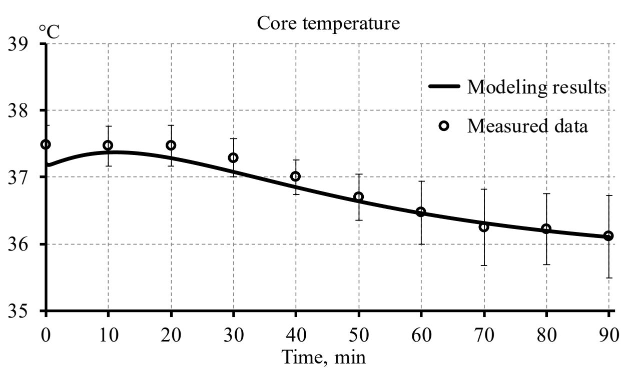


Fig. 1. Internal temperature: marker — measured data [30]; solid line — simulation results

Table 2 compares the simulation results with the mean internal body temperature measured in humans [30]. The initial internal temperature values differ by 0.3°C between the human and simulation results. This discrepancy (37.2°C modeled vs. 37.5°C measured) is expected, as the model shows the mean internal body temperature, while the study measured the stomach temperature. Both temperatures show the same cooling trend; after 90 minutes of exposure to cold water, they were 36.1°C.

Table 2

Comparative analysis of modeling results with measured data

Time, min	Internal temperature, °C		Temperature difference, °C
	Simulation results	Measured data [30] – mean ± SD	
0	37.20	37.49 ± 0.29	–0.29
10	37.37	37.47 ± 0.3	–0.10
20	37.29	37.47 ± 0.31	–0.18
30	37.08	37.29 ± 0.29	–0.21
40	36.85	37 ± 0.26	–0.15
50	36.64	36.7 ± 0.35	–0.06
60	36.46	36.47 ± 0.47	–0.01
70	36.31	36.25 ± 0.57	0.06
80	36.20	36.22 ± 0.53	–0.02
90	36.10	36.11 ± 0.62	–0.01
Average temperature difference, °C			–0.10
Standard deviation, °C			0.14
Student's t-test, *t*			2.16
Theil's index			0.003

The value of the Theil index approaches zero, indicating a high similarity between the predicted and observed values, and the Student's *t*-test shows $t = 2.16$ (degrees of freedom = 9, $p > 0.05$), indicating the absence of a statistically significant difference between the simulated and measured values of human internal body temperature.

5. 2. Client-server architecture

A multi-tier client-server architecture was designed, which provides logical and physical separation of computing resources (Fig. 2). The key advantage of such an architecture is that all computational logic associated with the thermal regulation model is executed on a remote server. The mobile application, in turn, is solely responsible for user interaction, data entry, and visualization of the results.

The client layer is represented by a mobile application for the Android operating system. The choice of this platform is justified by its dominant position in the mobile device market, and the use of the Java programming language makes it possible to ensure high performance and reliability of the client part.

The server layer, deployed in a cloud infrastructure, is implemented using a service-oriented approach. The Application Server, developed in Java, is responsible for processing requests via the REST API, managing data flows, and implementing authentication protocols. The computational core, implemented as a separate high-performance module in C++, encapsulates the mathematical model of human thermoregulation – Health Risk Prediction (HRP) [31, 32]. The data storage system is based on the MySQL relational database management system, which guarantees the integrity and consistency of users' personal data owing to support for ACID transactions.

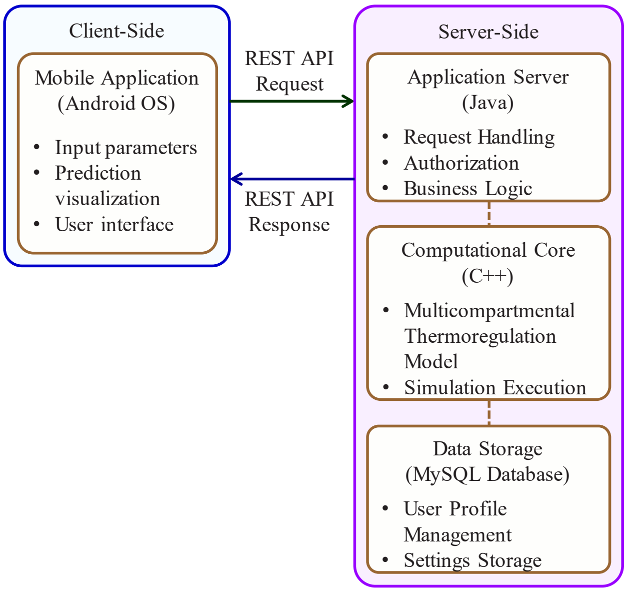


Fig. 2. Flowchart of the forecasting method

Through asynchronous request processing and a multi-threaded execution model, the server part is able to maintain stable operation under high loads, providing low latency for a significant number of simultaneous client sessions.

5. 3. Mobile application for predicting the human state in water

The graphical interface of the mobile application consists of data entry screens; prediction results display screens; and analysis screens. The data entry interface makes it possible to select the conditions of the water and air environment, immersion level, type of clothing (swimsuit or wetsuit), type of physical activity, and duration of human stay in the water (Fig. 3).

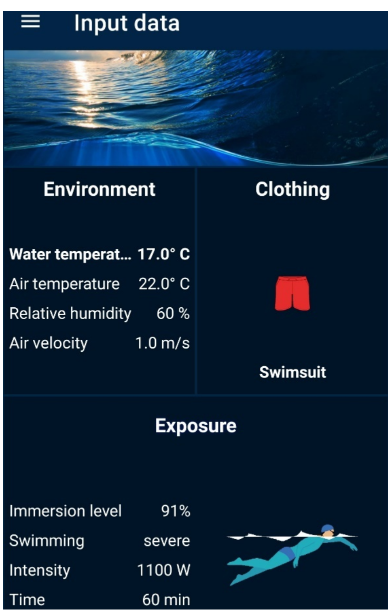


Fig. 3. Input of initial data

The application allows the user to choose the water temperature in the range of 10÷30°C and the level of immersion. It provides submersion, immersion and partial immersion (waist, knees and ankles deep) [33]. In the case of partial immersion, it is necessary to specify the air characteristics: temperature, humidity, and wind speed. The intensity and duration of physical activity in the water are set using sliders (Fig. 4).

In cold water, the application predicts the impact of protective clothing to prevent hypothermia (Fig. 5).

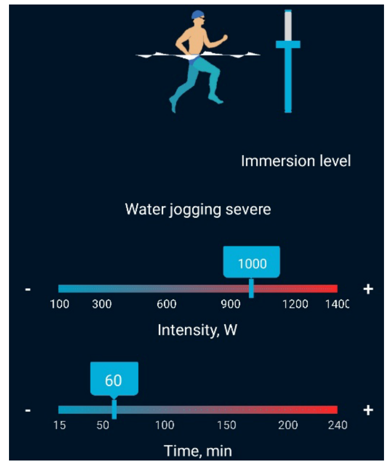


Fig. 4. Input the level of immersion, intensity, and duration of physical activity

Fig. 5. Choice the wetsuit

Modern wetsuits for these purposes are made of neoprene material, which has the following parameters: thermal insulation of 0.116 $m^2 \cdot °C/W$, thickness of 6 mm, and density of 170 kg/m^3 [34].

5. 4. Predicting of human functional state in water

5. 4. 1. The influence of swimming intensity on human thermophysiological responses

The dynamics of internal temperature of a man during swimming at the intensity of 300 W and 600 W in cold water with a temperature of 10°C in a regular swimsuit are shown in Fig. 6.

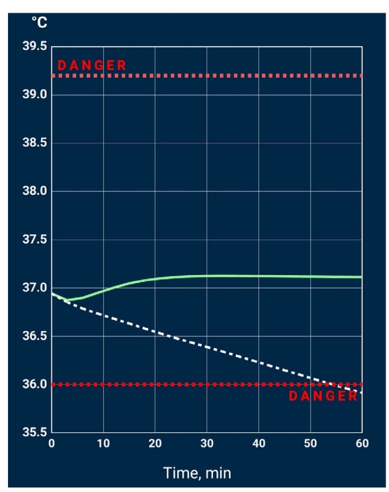


Fig. 6. Dynamics of internal temperature of man during swimming: white dotted line – 300 W; green solid line – 600 W

The immersion level is up to the neck, the air temperature is 15°C, the swimming duration is 60 minutes. At the end of swimming at a speed of 1.5 km/h (300 W), the internal body temperature decreased to 35.9°C. With an intensity of 600 W, which corresponds to a swimming speed of 2.3 km/h, the internal temperature remained at 37.1°C.

5. 4. 2. The effect of protective clothing on human thermophysiological responses in cold water

According to the standards adopted by World Aquatics (2023), swimming competitions in open water at water temperatures of 17°C and below should be held in wetsuits [35].

To assess the effect of a wetsuit in cold water, a comparative modeling of human thermophysiological responses was conducted: while standing still (150 W) and while swimming (1100 W). Without protective clothing, hypothermia occurs when standing in water at a temperature of 17°C, the body temperature decreases to 35.9°C in 60 minutes (Fig. 7). The use of a wetsuit provides insignificant changes: the internal body temperature decreased to 36.6°C (the initial value was 36.9°C). The effect of protective clothing is obvious.

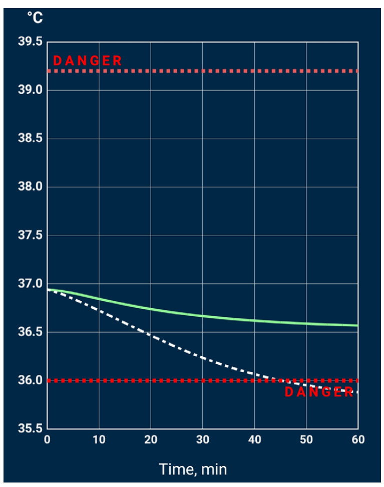


Fig. 7. Dynamics of internal temperature while standing in water (150 W) without a wetsuit – white dashed line; with a wetsuit – green solid line

The effect of activity intensity on the thermal responses of a man without a wetsuit and in a wetsuit is shown in Fig. 8. Input data for modeling: water temperature 17°C, swimming intensity 1100 W, duration 60 minutes. Swimming intensity 1100 W corresponds to a crawl swimming speed of 1.2 m/s. Without protective clothing, the internal body temperature reached a steady value of 38.1°C in 15 minutes. In a wetsuit, the internal temperature constantly increases and at the end of 60 minutes its value reaches 39.2°C.

The mobile application has a simulation results analysis screen (Fig. 9). The interactive control element "Scroll time" makes it possible to assess the risks of developing hypothermia or hyperthermia. On the "Temperature" scale, physiologically safe ranges are marked in green (Fig. 9, *a*), the risk of hypothermia is marked in blue, and the risk of hyperthermia is marked in red (Fig. 9, *b*).

The results of modeling the effects of physical activity and wetsuit are given in Table 3. It contains data on cardiovascular responses, heat generation during shivering, and heat transfer to water by conduction and convection.

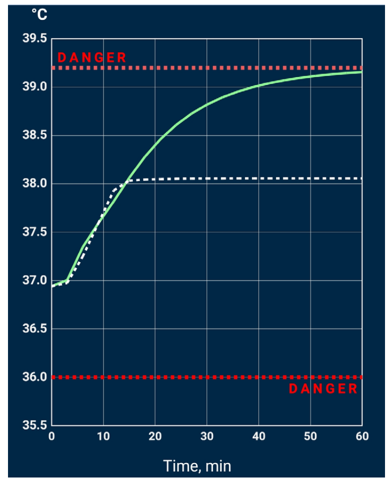
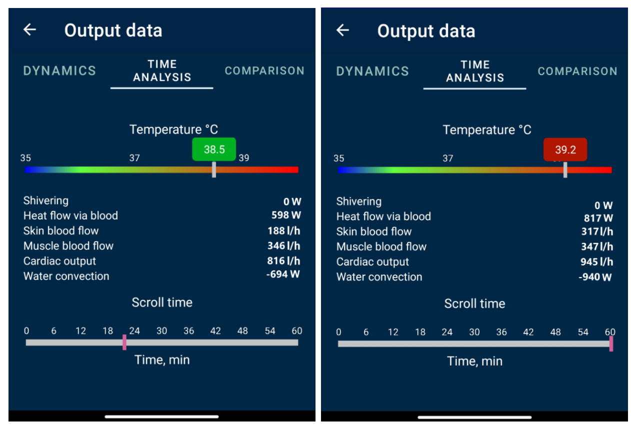


Fig. 8. Dynamics of human internal temperature while swimming (1100 W) without a wetsuit – white dotted line; in a wetsuit – green solid line



a *b*

Fig. 9. Time analysis of core temperature changes and thermoregulatory responses of swimmer in wetsuit: *a* – swimming intensity of 1100 W for 21 min is safe; *b* – there is a risk of hyperthermia in 60 min

Table 3

Comparison of thermal responses during rest and swimming in a swimsuit and a wetsuit. Immersion time – 60 min, water temperature – 17°C

Activity	Rest (150 W)		Swimming (1100 W)	
Clothing	Bathing	Wetsuit	Bathing	Wetsuit
Shivering, W	307	47	16	0
Heat exchange through blood, W	40	22	391	817
Blood flow in skin, l/h	3	3	18	317
Blood flow in muscles, l/h	118	58	350	347
Cardiac output, l/h	403	342	650	945
Heat exchange with water, W	–438	–157	–1009	–940

The application provides information on the safety during rest and activity in water for the appropriate decisions. At the same time, the application may be of interest for scientific research related to the effects of cold water. It provides additional data that characterizes the thermal responses of a man during activity in the water.

6. Discussion of method for predicting of human state in cold water

Our results showed a high level of consistency between the model predictions and observations obtained from volunteers during immersion in cold water, with a standard deviation of the human internal temperature of 0.14°C and the absence of statistically significant deviations ($p > 0.05$) (Fig. 1, Table 2). This result confirms the reliability of the proposed model and its suitability for practical application.

The study implemented the integration of a multicompartmental model of thermoregulation with a mobile application. The designed multi-level client-server architecture (Fig. 2) provides an opportunity to combine the reliability of modeling with the ease of use of a mobile application for assessing the risks of hypothermia and overheating.

An important feature of the developed application is the ability to comprehensively take into account the conditions of the water and air environment, the intensity of physical activity, the characteristics of protective clothing, and the level of immersion (Fig. 3–5). The mobile application developed on the basis of the model bridges the gap between modern thermophysiological modeling and practical m-health solutions. Unlike existing information applications [13], which provide information about the state of the environment, the proposed solution is able to predict the human physiological responses in water, taking into account his activity and protective clothing. Compared to reactive systems [14–17], which are triggered only at the moment of critical events, the proposed application provides the opportunity to assess risks in advance by integrating a complex mathematical model. Unlike expert models [18, 19], which are intended exclusively for use by specialists, this solution is designed as a personal tool for the general public. Unlike UKNIIS [20], which is limited to already documented cases, the proposed solution makes it possible to get a forecast of the dynamics of the internal body temperature and predict the risk of hypothermia.

The simulation conducted using the developed mobile application showed that with moderate physical activity (300 W) in water at a temperature of 10°C, the internal body temperature decreases and there is a risk of hypothermia, while with a high level of activity (600 W), the human body is able to maintain heat balance (Fig. 6).

The simulation results confirm the significant role of protective clothing (wetsuit) in maintaining a man heat balance while in cold water. During passive immersion (150 W) in water at a temperature of 17°C, the model predicts the onset of hypothermia within 60 min without using a wetsuit: the internal temperature drops below 36°C. In contrast, using a wetsuit stabilizes the internal temperature, its decrease is only 0.3°C over the same period (Fig. 7). This result is consistent with the World Aquatics [35] recommendations that require wetsuits to be worn in open water competitions at temperatures of 17°C or lower. The results provide quantitative evidence that wetsuits significantly reduce heat loss during low-intensity or rest periods in cold water environments.

At the same time, the modeling makes it possible to identify potential risks associated with the use of protective clothing at high intensity loads. During swimming at an intensity of 1100 W, which corresponds to a speed of approximately 1.2 m/s in the crawl style, the internal temperature without protective clothing quickly stabilizes at 38.1°C. In contrast, in the case of wetsuit use, the model predicts a continuous increase in internal temperature, reaching 39.2°C after 60 minutes (Fig. 8). This suggests that while wetsuits are essential to prevent hypothermia in cold water, they may increase the likelihood of hyperthermia during prolonged or intense exercise. The findings highlight the need to consider both environmental conditions and physical activity-related factors when compiling safety recommendations for open water swimming.

The limitations of our study are explained by the fixed ranges of environmental parameters (water/air temperature, humidity, wind speed) and characteristics of human physical activity (Fig. 3, 4). Another limitation is the incomplete consideration of the properties of protective clothing (Fig. 5) used in water. This is due to the insufficient amount of biophysical data and characteristics of the materials from which modern wetsuits are made. Updating and adopting new standards for such clothing could make it possible to supplement the capabilities of the application.

A promising direction to further advance our method is to expand its functionality to simulate other extreme conditions, such as high temperatures, hypoxia, and high altitudes. The inclusion of additional physiological parameters such as cardiovascular indicators, metabolic activity, hydration status and cognitive functions will increase the ability of the method to predict human resistance and physiological risks in different states. This addition will enable comprehensive monitoring of human safety in professional, sports, and recreational settings. In addition, the application's integration with modern wearable technologies and personalized databases could provide adaptive feedback and individual recommendations.

7. Conclusions

1. We have validated the mathematical model by comparing the simulation results with published observation data on volunteers. Statistical analysis confirmed the absence of a significant difference between the model and measured values of internal body temperature ($p > 0.05$), which proves the predictive accuracy of our model.

2. The multilevel client-server architecture has been designed, which enables the integration of the mathematical model with the mobile application. Performing resource-intensive calculations on the server infrastructure ensures the availability of complex predictive modeling on mobile devices.

3. The mobile application has been developed for predicting temperature risks, which ensures that the conditions of the water and air environment, the level of immersion, the intensity of physical activity, and the characteristics of protective clothing are taken into account. The application provides personalized recommendations on the safe duration of stay in the water, which extends the functionality of mobile technologies beyond conventional monitoring.

4. The simulation results showed that the risk of hypothermia depends on the water temperature, the intensity of physical activity, and the protective clothing. It was shown that in water of 10°C, moderate physical activity (300 W) is insufficient to maintain heat balance and hypothermia (35.9°C) occurs, while high activity (600 W) makes it possible to stabilize the internal temperature (37.1°C). During passive stay (150 W) in water of 17°C without a wetsuit, hypothermia (< 36°C) occurs within 60 min, while the wetsuit stabilizes the temperature (decrease of 0.3°C). At the same time, during intensive swimming (1100 W) in water of 17°C, the wetsuit leads to the risk of

hyperthermia, increasing the internal temperature to 39.2°C, in contrast to stabilization at 38.1°C without it.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

AI model used: ChatGPT 5.1.

AI was used in Chapter 2 "Literature Review and Problem Statement" to check the grammar and vocabulary of the written text.

The grammatical and lexical errors detected by AI were checked and corrected manually by the authors.

The result provided by the AI tool did not affect the conclusions in this study.

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