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KHVOSTIVSKYI MYKOLA
Ternopil Ivan Puluj National Technical University
https://orcid.org/0000-0002-2405-4930
e-mail: hvostivskyy@tntu.edu.ua
UNIIAT SERHII
Ternopil Ivan Puluj National Technical University
https://orcid.org/0009-0005-3165-9937
e-mail: uniatsergiy@gmail.com

SIMULATION MODELING OF THE PULSE WAVE DURING PHYSICAL LOAD AS A MEANS OF VERIFYING SIGNAL PROCESSING METHODS

The article presents a mathematical and simulation model of the human pulse signal during physical load, which can be used to verify digital signal processing methods in biomedical applications. The relevance of the research arises from the need to develop controlled models that reproduce physiologically consistent cardiovascular dynamics without the necessity of complex experimental procedures. The proposed approach integrates parametric modeling of heart rate variability, temporal discretization of observation, and morphological synthesis of pulse waves by convolving discrete cardiac impulses with a vascular response kernel. The model is implemented in the MATLAB environment, enabling numerical experiments, parameter variation, and simulation of different physiological conditions ranging from rest to active workload.

Heart rate dynamics are described by a piecewise-smooth function that includes rest, acceleration, steady-load, and recovery phases with continuous transitions corresponding to the real physiological adaptation of the cardiovascular system. Cardiac beats are simulated through phase integration of the instantaneous frequency, where each crossing of an integer phase value denotes a new cardiac impulse. The morphology of the pulse wave is modeled as a superposition of forward and reflected components, whose amplitudes, delays, and asymmetry determine the characteristic dual-peaked shape typical of pulse signals. This allows the model to reproduce waveform transformations under varying load conditions.

The resulting signal is physiologically plausible, parameter-controlled, and suitable for verifying algorithms of peak detection, filtering, adaptive segmentation, and heart rate variability (HRV) analysis. The model demonstrates high reproducibility, stability, and simplicity of implementation. Using simulation modeling as a verification tool reduces dependence on real clinical experiments and provides standardized conditions for testing digital signal processing techniques. The proposed work contributes to the development of bioengineering models of cardiovascular dynamics and to the enhancement of intelligent monitoring systems for human physiological parameters.

Keywords: *pulse signal, simulation modeling, physical load, heart rate, MATLAB, algorithm verification.*

ХВОСТІВСЬКИЙ МИКОЛА
УНІЯТ СЕРГІЙ
Тернопільський національний технічний університет імені Івана Пулюя

ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ПУЛЬСОВОГО СИГНАЛУ ПІД ЧАС ФІЗИЧНОГО НАВАНТАЖЕННЯ ЯК ЗАСІБ ВЕРИФІКАЦІЇ МТОДІВ ОБРОБКИ

У статті представлено математичну та імітаційну модель пульсового сигналу людини під час фізичного навантаження, що може бути використана для верифікації методів цифрової обробки біомедичних сигналів. Актуальність роботи зумовлена потребою у створенні контрольованих моделей, які дозволяють відтворювати фізіологічно обґрунтовану динаміку серцево-судинної системи без проведення складних експериментів. Запропоновано підхід, який поєднує параметричне моделювання частоти серцевих скорочень, часову дискретизацію процесу спостереження та морфологічне формування пульсових хвиль шляхом згортки окремих серцевих імпульсів із ядром судинної відповіді. Модель реалізовано у середовищі MATLAB, що забезпечує можливість чисельного експерименту, варіації параметрів навантаження та відтворення різних фізіологічних станів організму.

Частота серцевих скорочень у моделі описується кусково-гладкою функцією, що включає фази спокою, наростання, стабільного навантаження та відновлення, із плавними переходами між ними, що відповідає реальній реакції серцево-судинної системи. Імітація серцевих ударів базується на інтегруванні миттєвої частоти для формування фазової змінної, моменти переходу якої через цілі значення визначають появу окремих серцевих імпульсів. Морфологія пульсової хвилі формується як суперпозиція прямої та відбитої компонент, параметри яких контролюють амплітуду, затримку та асиметрію сигналу. Такий підхід дозволяє відтворити характерну форму пульсового сигналу, а також моделювати її зміну під дією навантаження.

Отриманий сигнал є фізіологічно достовірним, має контрольовані параметри і придатний для перевірки алгоритмів виявлення піків, фільтрації, адаптивної сегментації та оцінювання варіабельності серцевого ритму (HRV). Модель відзначається простотою реалізації, стабільністю та високою відтворюваністю результатів. Використання імітаційного моделювання як засобу верифікації дозволяє зменшити потребу в реальних клінічних експериментах, забезпечуючи стандартизовані умови для тестування методів цифрової обробки. Представлена робота створює підґрунтя для подальшого розвитку біоінженерних моделей серцево-судинної динаміки та вдосконалення інтелектуальних систем моніторингу фізіологічних параметрів людини.

Ключові слова: *пульсовий сигнал, імітаційне моделювання, фізичне навантаження, частота серцевих скорочень, MATLAB, верифікація алгоритмів.*

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Problem Statement. Analysis of Research and Publications

The pulse signal is one of the key biomedical indicators that characterizes the functional state of the human cardiovascular system. Its analysis makes it possible to assess heart rate, vascular tone, arterial elasticity, and the body's response to external influences. Currently, pulse signals, particularly photoplethysmograms (PPG), are widely used for non-invasive monitoring of patients' conditions in medical monitoring systems, as well as in portable health-tracking devices.

However, the processing of real biomedical signals remains challenging due to the presence of noise, motion artifacts, and variability of physiological parameters, which necessitates the development of controlled models for testing and comparing analysis algorithms.

The verification of digital pulse signal processing algorithms requires the availability of representative test data that reflect various physiological states – from rest to active physical exercise. Since obtaining such data under real conditions involves complex experiments, significant time, and compliance with ethical requirements, simulation modeling of pulse signals has become a relevant research direction. It serves as an effective means for testing the performance of peak detection, filtering, and heart rate variability estimation algorithms [1-3].

In this context, pulse signal simulation has become particularly relevant, as it enables the generation of artificial data with controllable parameters for testing digital signal processing methods.

Current scientific publications identify several main approaches to pulse signal modeling:

– Hemodynamic models developed by J. Alastruey and co-authors [4] are based on solving wave propagation equations within the vascular system and take into account reflection effects and flow nonstationarity. Such approaches are physiologically accurate; however, they require substantial computational resources.

– Empirical models, including the works of M. Elgendi [5] and Q. Tang [6], represent the shape of the pulse wave as a sum of analytical functions – typically two or three Gaussian or log-normal components corresponding to the forward and reflected waves. These approaches are simple to implement and suitable for generating synthetic pulse signals.

– Stochastic models described by L. Sörnmo and P. Laguna [7] treat the pulse signal as a random process with predefined spectral characteristics and allow for the modeling of noise components.

– Hardware-software simulators presented in the study by C. Guo and colleagues [8] are used for calibrating pulse wave velocity measurement devices and verifying the metrological characteristics of monitoring systems.

In the Ukrainian scientific school, pulse signal simulation has been advanced in the works of L. Khvostivska, M. Khvostivskyi, H. Osukhivska, and H. Shadrina [1-3]. The researchers have proposed parametric models of human vascular pulse signals that account for the temporal structure of the wave and phase shifts, as well as models of circadian pulse variations for verifying cardiovascular activity monitoring algorithms. These approaches ensure consistency between physiological parameters and the mathematical descriptions of the signals.

Despite considerable progress, most known models do not account for dynamic changes in heart rate and pulse wave morphology during physical activity, which is critically important for evaluating the performance of algorithms under transitional conditions (acceleration, stabilization, recovery). Furthermore, the influence of psycho-emotional stress on vascular tone remains insufficiently studied, although it also alters the amplitude–phase characteristics of the pulse signal.

Objectives of the Study

The aim of this study is to develop and mathematically justify a simulation model of the pulse signal during physical activity, which accounts for changes in heart rate, pulse wave morphology, and noise components, and can be used for the verification of biomedical signal processing methods.

Time-Dependent Heart Rate Model

Heart rate $HR(t)$ is a physiological parameter that reflects the number of heartbeats per unit of time. It is a variable quantity determined by two main factors:

1. Physiological state phase of the body (rest, exertion, recovery;
2. Regulatory response of the autonomic nervous system – sympathetic (increases HR) and parasympathetic (decreases HR).

The typical time course of heart rate during physical exercise consists of the following phases:

– Rest phase – a stable heart rate, typically 55-70 beats per minute (bpm);
– Rising phase – gradual increase in heart rate during the first seconds after the onset of activity;
– Exercise phase – maintenance of a high, nearly constant heart rate during active physical activity;
– Recovery phase – exponential decrease in heart rate after the cessation of activity;
– Return to rest – stabilization of heart rate at a level close to the initial value.

The model assumes that the heart rate response to physical activity occurs smoothly, without abrupt jumps. Therefore, its behavior is described by a piecewise-smooth function of time, composed of four phases: rest; gradual rise to the peak; steady exercise phase; and gradual exponential recovery.

Before the onset of activity ($t<t_{load\_start}$), the heart rate remains constant

$$HR(t) = HR_{rest}, \tag{1}$$

where HR_{rest} – Resting heart rate (HR at rest).

This phase represents the baseline level of cardiac activity corresponding to the resting state.

After the onset of activity, HR gradually increases from the baseline value to the peak (phase 2 – gradual rise of HR).

During the transition phase from rest to exercise, the heart does not increase HR instantaneously, as this process is regulated by the autonomic nervous system. Therefore, instead of a sharp transition, a smooth rising function in the form of a half-cosine interpolator is used to ensure physiological gradualness.

The expression for HR changes during phase 2, using a half-cosine interpolator, is given by:

$$HR(t) = HR_{rest} + (HR_{peak} - HR_{rest})\frac{1-cos\left(\pi\frac{t-t_{load\_start}}{T_{up}}\right)}{2}, \ t_{load\_start} \le t < t_{load\_start} + T_{up}, \quad (2)$$

where HR_{peak} – Maximum HR during exercise;

T_{up} — duration of the rise phase (time required for the heart to reach peak HR);

t_{load_start} – exercise onset;

Physiologically, phase 2 corresponds to the gradual activation of the sympathetic nervous system, with the heart responding after a delay of several seconds following the onset of physical activity.

After the rise phase, the heart operates in a steady state at maximum HR throughout the active phase (phase 3 – steady exercise):

$$HR(t) = HR_{peak}, \ t_{load\_start} + T_{up} \le \ t < T_{load}, \quad (3)$$

where T_{load} – duration of exercise (phase of stable high HR);

During this period, the heart rate is stabilized, corresponding to a quasi-stationary state of physical activity, where a temporary balance between sympathetic activation and physiological adaptation is maintained.

After the cessation of exercise, the heart gradually slows down, approaching the initial level (phase 4 – exponential recovery). This process is well described by an exponential decay law, which is frequently used in physiological recovery models:

$$HR(t) = HR_{rest} + (HR_{peak} - HR_{rest})e^{-\frac{(t-t_{load\_end})}{\tau_{rec}}}, \ t \ge t_{load\_end}, \quad (4)$$

where $t_{load\_end} = t_{load\_start} + T_{up} + T_{load}$.

τ_{rec} – recovery time constant, reflecting the rate of physiological adaptation (low values indicate rapid recovery, while high values – depending on physical fitness – indicate slower recovery, which may be a sign of fatigue or pathology.

All phases are combined into a single analytical equation in the form of a generalized piecewise-smooth function, with distinct expressions for each phase:

$$HR(t) = \begin{cases} HR_{rest}, & t < t_{load\_start} \\ HR_{rest} + (HR_{peak} - HR_{rest})\frac{1-cos\left(\pi\frac{t-t_{start}}{T_{up}}\right)}{2}, & t_{load\_start} \le t < t_{load\_start} + T_{up} \\ HR_{peak}, & t_{load\_start} + T_{up} \le t < t_{load\_end} \\ HR_{rest} + (HR_{peak} - HR_{rest})e^{-\frac{(t-t_{load\_end})}{\tau_{rec}}} & t \ge t_{load\_end} \end{cases}, \quad (5)$$

where HR_{rest} – Resting HR; HR_{peak} – Maximum HR during exercise;

T_{up} – duration of the rise phase (time required for the heart to reach peak HR);

T_{load} – duration of the exercise phase (phase of sustained elevated HR;

T_{load} – duration of the exercise phase (phase of stable high HR);

t_{load_start} – time of exercise onset;

$t_{start}+T_{up}$ – time to peak HR;

$t_{load\_end}=t_{start}+T_{up}+T_{load}$ – end of exercise.

The $HR(t)$ model reproduces a realistic cardiac response to physical activity. The HR(t) function serves as a «control signal» that defines the temporal structure of heartbeats, the shape and duration of each cycle, and the overall energy profile of the signal when modeling the pulse wave.

Conversion of instantaneous heart rate into cardiac pulses

For mathematical modeling of heartbeat occurrences at a variable rate, the concept of instantaneous cardiac phase $\phi(t)$ is introduced. This dimensionless quantity increases over time at a rate proportional to the instantaneous heart rate:

$$\frac{d\varphi}{dt} = f_H(t), \quad (6)$$

i.e:

$$\varphi(t) = \int_0^t f_H(\tau)d\tau. \quad (7)$$

Interpretation of cardiac phase:

– $\phi(t)$ indicates the number of cardiac cycles that have elapsed since the beginning of observation;
– When $\phi(t)$ increases by 1, it indicates that one additional heartbeat has occurred;
– Therefore, each heartbeat corresponds to the point in time when $\phi(t)$ passes through an integer value.

$$\varphi(t_n) = n, \ n = 1,2,3, \ldots, \quad (8)$$

where t_n – time of occurrence of the n-th heartbeat.

The integral in discrete form is computed using cumulative integration (analogous to a numerical integrator):

$$\varphi_i = \sum_{k=1}^{i} f_H(t_k)\Delta t, \quad (9)$$

Afterward, the sequence of pulse timing moments can be determined according to the following condition:

If $[\varphi_i] < [\varphi_{i+1}]$, a heartbeat occurs at the moment t_{i+1}. (10)

In other words, when the phase crosses the next integer value, a pulse is generated. This provides us with a discrete sequence of pulses:

$$I(t_i) = \begin{cases} 1, & якщо \ [\varphi_i] < [\varphi_{i+1}], \\ 0, & інакше. \end{cases} \quad (11)$$

Such a binary sequence $I(t)$ essentially simulates a «heartbeat spike» signal, where a value of one indicates the occurrence of a heartbeat, and zeros represent the absence of an event.

Since the instantaneous frequency $f_H(t)$ changes smoothly over time, the intervals between consecutive heartbeats:

$$RR_n = t_{n+1} - t_n. \quad (12)$$

are not constant and depend on the current value of $f_H(t)$.

Specifically:

$$RR_n \approx \frac{1}{f_H(t_n)}. \quad (13)$$

Thus, the $\phi(t)$ model automatically reproduces the physiological variability of heart rate – during an increase in HR (exercise), the RR_n intervals shorten, whereas during recovery they lengthen. In particular, the mathematical model $\phi(t)$ approximates the bioelectrical activity of the sinoatrial node, with the threshold of 1 serving as an analog of the action potential threshold of the cells

The transformation of instantaneous frequency $f_H(t)$ into phase $\phi(t)$ and discrete events (heartbeats) serves as a bridge between the continuous heart rate regulation model and actual pulse measurement

It allows the generation of a signal that reproduces the natural variability and adaptation of the heart to physical activity.

Model of a single pulse waveform (pulse core)

The pulse signal is not simply a periodic sequence of pulses; each pulse cycle contain:

– A forward wave, generated by the contraction of the left ventricle and propagating through the arterial system;

– A reflected wave, arising from the reflection of the pressure wave at peripheral resistances (e.g., vessel bifurcations, arterioles, etc.).

As a result, the shape of the pulse signal contains a first peak corresponding to the systolic rise, and a second peak – of the reflected wave, which arrives with a certain delay.

A single pulse can be described as a superposition of two decaying asymmetric waves:

$$h(t) = s_1(t) + A_r s_2(t), \quad (14)$$

where $s_1(t)$ – shape of a straight wave;

$s_2(t)$ – shape of the reflected wave;

$A_r \in [0,1]$ – relative amplitude of the reflected wave.

Each of these components is an asymmetric function that models the rapid rise and gradual decay characteristic of hemodynamic processes.

The forward wave $s_1(t)$ is described as a function in which the leading edge rises exponentially, while the decay follows a Gaussian or quasi-linear damping. This behavior can be approximately represented as the product of two functions:

$$s_1(t) = e^{\left(-\frac{t^2}{2\sigma_f^2}\right)}\left(1 - e^{\left(-\frac{t}{\sigma_r}\right)}\right). \quad (15)$$

where σ_r – time constant of the rise (indicating the rate of the systolic upstroke);

σ_f – decay parameter (defines the duration and slope of the diastolic downstroke.

The function $1 - e^{\left(-\frac{t}{\sigma_r}\right)}$ provides a gradual onset, avoiding abrupt transitions, while the factor $e^{\left(-\frac{t^2}{2\sigma_f^2}\right)}$ ensures decay after the peak

The result is a smooth asymmetric wave with a rapid rise and a slow decay, typical of a real systole.

The reflected wave is modeled similarly, but with a time delay τ_d and a reduced amplitude A_r. Its mathematical form is given by:

$$s_2(t) = e^{\left(-\frac{(t-\tau_d)^2}{2\sigma_{f2}^2}\right)}\left(1 - e^{\left(-\frac{t-\tau_6}{\sigma_{r2}}\right)}\right). \quad (16)$$

where τ_d – temporal delay of the reflected wave with respect to the forward wave;

σ_{r2}, σ_{f2} – the rise and decay parameters of the reflected wave (typically greater than those of the forward wave, resulting in a smoother profile).

Normalization and smoothing

To avoid a small dip between the peaks (which often occurs due to a simple sum of the two waves), the kernel shape is additionally smoothed. Mathematically, this can be represented as a convolution with a smoothing kernel $G(t)$:

$$h_s(t) = (h{*}G)(t), \quad (17)$$

where $G(t)$ – a narrow Gaussian filter that eliminates local dips and ensures smoothness of the first and second derivatives $\tilde{k}(t)$;

Subsequently, the amplitude is normalized:

$$h_n(t) = \frac{h_s(t)}{\max_t h_s(t)} = \frac{(h{*}G)(t)}{\max_t h_s(t)}. \quad (18)$$

which sets the wave's maximum to 1 and simplifies subsequent signal scaling.

The resulting kernel $h_n(t)$ is normalized, has two peaks — systolic and reflected — and preserves the smoothness of the first and second derivatives

Formation of the composite signal via convolution

Cardiac activity can be considered as a sequence of discrete events — each myocardial contraction (heart beat) generates a single pulse.

If we denote the time t_n as the occurrence of the n-th cardiac contraction, the cardiac rhythm can be modeled as a pulse train:

$$\delta_H(t) = \sum_{n=1}^{N} \delta(t - t_n). \tag{19}$$

where $\delta(t)$ – dirac delta function, which mathematically represents an instantaneous event (heart beat).

The function $\delta_H(t)$ describes the temporal structure of the cardiac rhythm (i.e., the precise timing of contractions). Mathematically, the process of superimposing individual pulse impulses is represented as the convolution of the pulse train with the pulse response kernel $h_n(t)$:

$$x(t) = A(\delta_H * h_n)(t) + b + n(t). \tag{20}$$

Or in expanded form:

$$x(t) = A\sum_{n=1}^{N} h_n(t - t_n) + b + n(t). \tag{21}$$

where A – amplitude scaling coefficient;

b – baseline signal level;

n(t) – noise component, $n(t) \sim N(0, \sigma_{noise}^2)$.

The pulse wave kernel $h_n(t)$, which describes the temporal profile of a single pulse response to one cardiac contraction, can be interpreted as the impulse response of the vascular system – that is, the arterial system's reaction to a unit 'input' in the form of a heartbeat. Summarizing the previous considerations, the overall form of the complete simulated pulse signal can be expressed as:

$$x(t) = A\sum_{n=1}^{N}\left[e^{\left(-\frac{t^2}{2\sigma_f^2}\right)}\left(1 - e^{\left(-\frac{t}{\sigma_r}\right)}\right) + A_r e^{\left(-\frac{(t-\tau_d)^2}{2\sigma_{f2}^2}\right)}\left(1 - e^{\left(-\frac{t-\tau_{\text{в}}}{\sigma_{r2}}\right)}\right)\right] + b + n(t). \tag{22}$$

where A – amplitude scaling coefficient (determines the strength of the pulsations);

A_r – reflected wave relative amplitude;

σ_r, σ_f – parameters of the rise and decay rates for the forward wave;

σ_{r2},σ_{f2} – corresponding parameters for the reflected wave;

τ_d – time delay between the forward and reflected waves;

b – constant baseline signal representing the mean arterial pressure, establishing the fundamental «pulse line», i.e., the average vascular pressure;

$n(t)$ – additive noise ($n(t) \sim N(0, \sigma_{noise}^2)$) representing micromovements, electrical artifacts, and other interferences.

Thus, equation (22) represents a generalized simulation model of the pulse signal, capturing both the temporal structure of cardiac impulses and the morphological features of the wave.

The parameters A, A_r, σ_r, σ_f, τd, b, σ_{noise} allow the model to be adjusted for various physiological or experimental conditions.

Algorithm for simulating the pulse signal during physical exercise

Figure 1 shows the algorithm for simulating the pulse signal during physical exercise. The algorithm reproduces changes in heart rate during physical exercise by generating a sequence of cardiac impulses corresponding to the phases of rest, activity, and recovery. These impulses are then convolved with the vascular response kernel to form a realistic pulse signal with characteristic systolic and reflected waves.

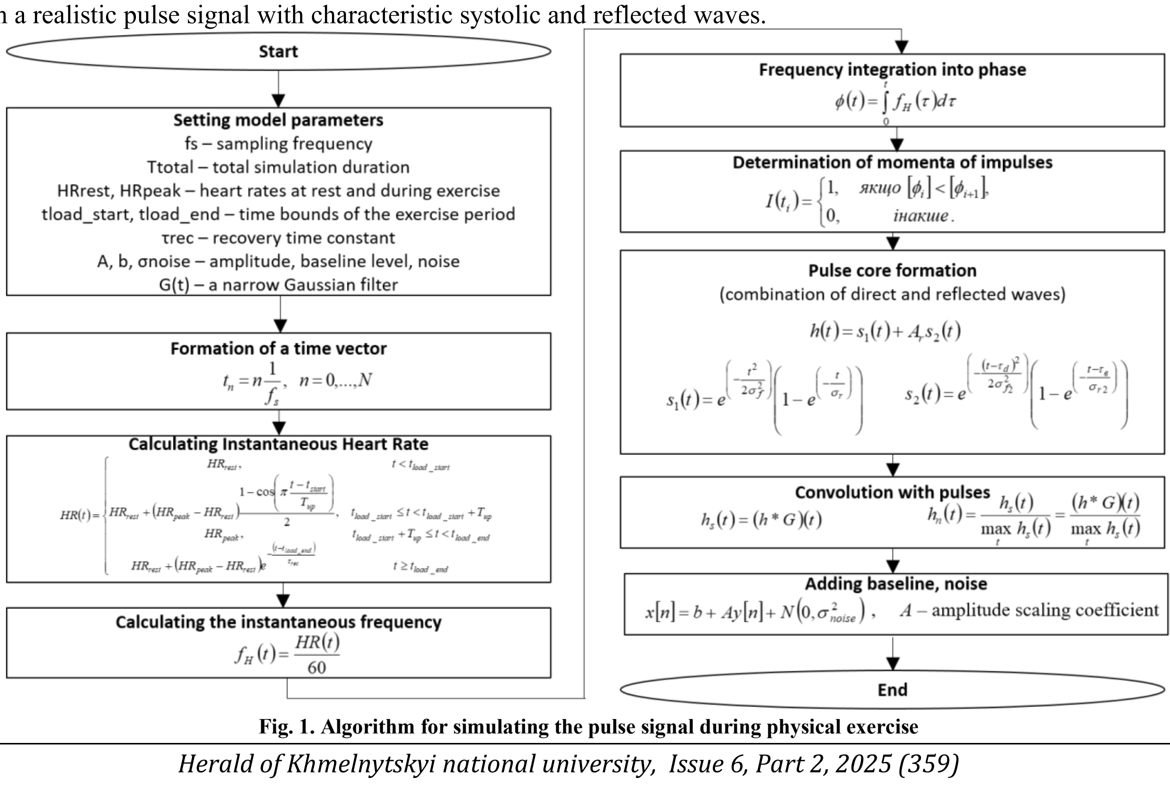

Fig. 1. Algorithm for simulating the pulse signal during physical exercise

Simulation result of the pulse signal during physical exercise

Figure 2 shows the overall view of the simulated pulse signal in the MATLAB environment, while Figure 3 presents a segment of the signal during the transition from the resting state to physical exercise.

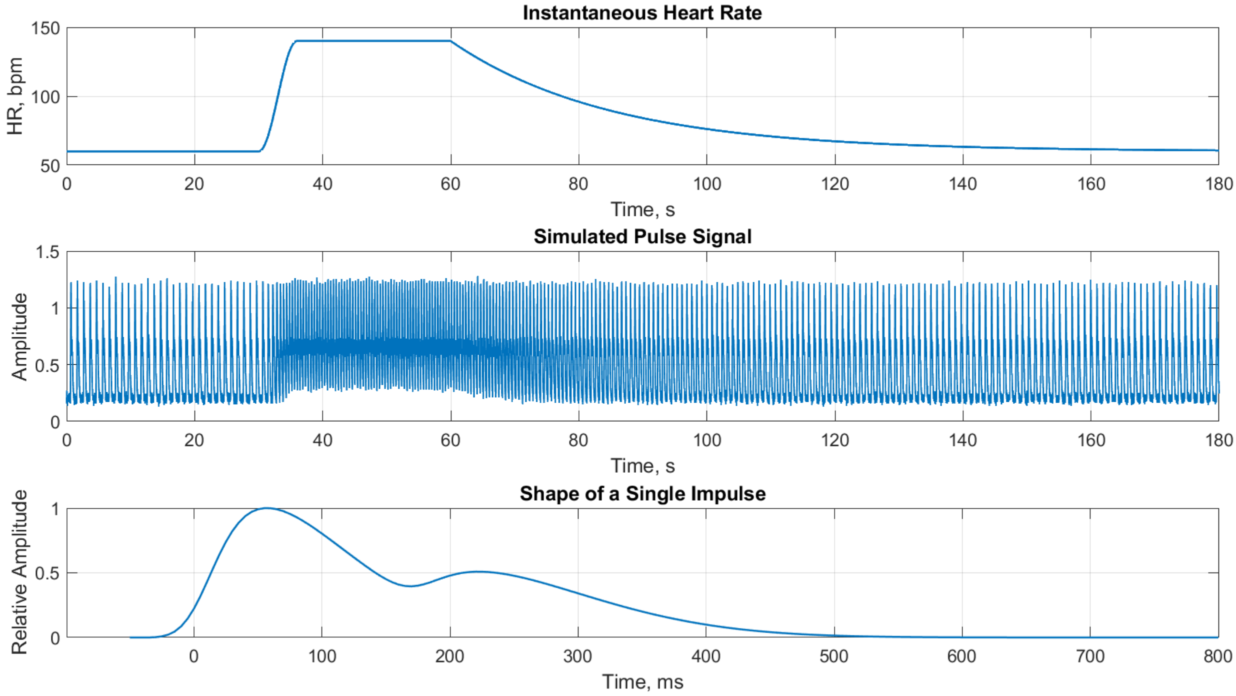

Fig. 2. Result of pulse signal simulation in MATLAB

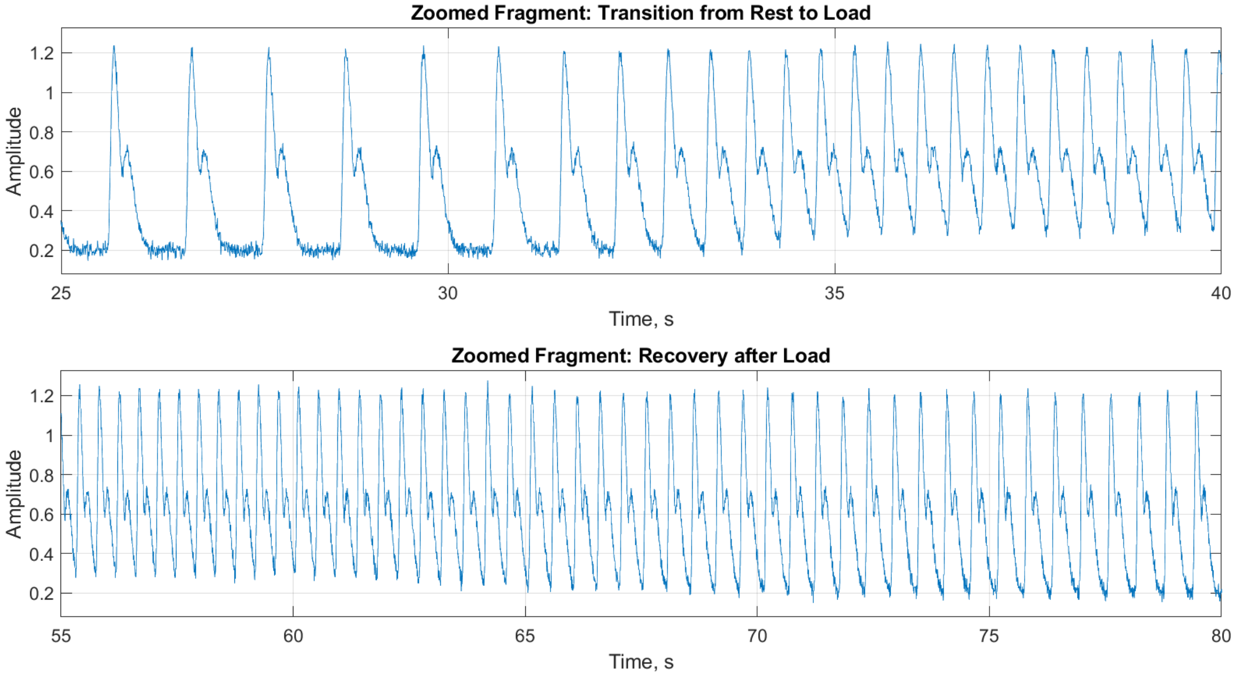

Fig. 3. Segment of the signal during the transition from rest to exercise

Analysis of the obtained curves (Figs. 2-3) shows that the model accurately reproduces the characteristic shape of the pulse signal, with pronounced systolic and reflected peaks, and also demonstrates a physiologically plausible dynamics of heart rate. In particular, during the transitional phase, a clear shortening of the intervals between successive pulses is observed, corresponding to an increase in heart rate, while the morphology of individual waves remains stable without waveform distortions. This indicates a correct implementation of phase integration of the instantaneous frequency and convolution with the vascular response impulse.

The behavior of the simulated signal is consistent with known physiological patterns – a gradual increase in heart rate at the onset of exercise, stabilization during sustained activity, and the absence of non-physiological artifacts. Thus, the model demonstrates a high degree of adequacy: its waveform, frequency dynamics, and phase structure correspond to real signals. The obtained results confirm the suitability of the model as a test tool for verifying digital pulse signal processing algorithms (peak detection, filtering, segmentation, HRV analysis), as well as for simulating various physiological states of the body under controlled conditions.

Conclusions

As a result of the conducted study, a mathematical and simulation model of the human pulse signal has been developed, which reproduces the physiologically plausible dynamics of the cardiovascular system during physical exercise. The model is based on phase integration of the instantaneous frequency and convolution of the pulse train with the vascular response impulse, ensuring accurate representation of the temporal structure of cardiac impulses and the morphology of the pulse wave. Implementation in the MATLAB environment enabled the generation of signals with controlled parameters, accurately reflecting the characteristic phases of cardiovascular response – rest, onset, steady-state exercise, and recovery – as well as the typical two-peaked shape of the pulse signal.

The obtained results demonstrate the high adequacy of the model and its suitability for verifying digital biomedical signal processing methods, including filtering, peak detection, adaptive segmentation, and heart rate variability analysis. Using simulation modeling as a tool for algorithm testing allows a significant reduction in the volume of real experimental studies and provides standardized testing conditions. The developed model can serve as an effective foundation for further development of bioengineering methods for cardiovascular dynamics analysis and for creating intelligent systems for monitoring human physiological parameters.

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