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DIMENSIONAL ANALYSIS MODEL FOR ANALYTICAL EVALUATION OF PROPULSION FORCE IN SPORTS ACTIVITIES

Мета. *Модель аналізу розмірностей використовується для аналітичного вираження залежності фізичної величини від низки експериментально отриманих фізичних параметрів,. Таким чином, використовуючи метод аналізу добуткурозмірностей, у цій роботі аналітично визначено вираження рушійної сили тіла людини в спортивній діяльності.* ***Методи****. Метод аналітичного моделювання з використанням експериментальних спостережень.* ***Результати****. Експериментальними спостереженнями як авторів, так і зі спеціальної літератури визначено швидкість руху, відстань, на яку здійснюється рух, тривалість руху, вагу тіла та вік індивіда як основні параметри, що впливають на рушійну силу. Метод передбачає вибір незалежних або фундаментальних розмірів, за допомогою яких* *формуються безрозмірні пропорції як для рушійної сили, так і для інших фізичних параметрів, розмірність яких залежить від фундаментальних розмірів. Для випадку, проаналізованого в цій статті, основними величинами були пройдена відстань, тривалість руху та вага тіла людини. Методом добутку розмірностей було отримано аналітичний вираз рушійної сили як добутка фізичних параметрів, розмірності яких є основними, і функцією, визначеною за допомогою як залежних фізичних параметрів, так і деяких незалежних, функцією, визначеною експериментально. На основі спеціальної літератури визначено функцію залежності залежних і незалежних фізичних параметрів, що дозволяє чисельне моделювання.* ***Висновок****. Метод добутку розмірностей, представлений у цій статті, можна використовувати в сфері спорту, зокрема тренувальному процесі, коли фізичну величину, що залежить від низки експериментально спостережуваних фізичних параметрів, потрібно виразити в розрахунковому виразі.*

Ключові слова: *рушійна сила, швидкість, вага тіла, дистанція бігу, вік*

Aim*. The dimensional analysis model is used to analytically express a physical quantity dependent on a number of physical parameters observed experimentally. Thus, using the method of dimensional analysis products, in this paper, the expression of the propulsion force of the human body, in sports activities, was analytically determined.* ***Methods****. Analytical modeling using experimental observations.* ***Results****. The experimental observations, both by the authors and from the specialized literature, have identified as the main parameters that influence the propulsion force, the speed of movement, the distance over which the movement is made, the duration of time for the movement, the mass of the human subject and the age of the individual. The method involves the choice of independent or fundamental dimensions, with the help of which dimensionless proportions are formed, both for the propulsion force and for the other physical parameters whose dimensions depend on the fundamental dimensions. For the case analyzed in this paper, the fundamental quantities were the distance traveled, the time duration for the movement and the mass of the human subject. With the help of the product method, the analytical expression of the propulsion force was obtained as a product between the physical parameters whose dimensions are fundamental and a function defined with the help of the dependent physical parameters and some of the independent ones, a function that is determined experimentally. Based on the specialized literature, the dependence function of the dependent and independent physical parameters was determined, so that the numerical simulation is possible.* ***Conclusion****. Te product method presented in this paper can also be used in the field of sports, when a physical quantity dependent on a number of experimentally observed physical parameters is desired to be expressed in a calculation expression.*

Key words: *propulsive force, velocity, body mass, running distance, age.*

Introduction

The propulsive force of the human body has a major effect on the dynamic stability of athletes, with either a positive effect, by obtaining the desired performance, or a negative effect, by the accidents that may occur. The propulsion force represents the previous component of the reaction force between the foot and the ground, the latter being easily determined experimentally. The force of reaction with the ground is used in all analyzes regarding walking or running, both for young people [1, 2, 3, 4, 5] and for elderly people [6, 7]. This reaction force and the propulsion force, also depends on the characteristics of the running surface, due to the corresponding elastic and frictional components [8, 9]. With the help of the ground reaction force, walking patterns [10, 11], athletic performance [12], impact loads, especially on the joints [13], the provocation of various musculoskeletal pathologies [14, 15] or the evaluation of different types of orthoses [16, 17]. Due to the fact that the measurements reflect individual values, statistical models were also used for generalization. Thus, various statistical techniques were used, such as principal component analysis and functional data analysis. Principal component analysis is a technique to reduce large data matrices into orthogonal principal components, which can explain the major modes of variation in the data set [18, 19, 20, 21]. Functional data analysis treats the entire data set as a function defined with a finite discrete time point [22].

This work aims to present an analytical-experimental modeling method based on dimensional analysis [23]. Dimensional analysis provides a method of reducing complex physical problems to their simplest form before obtaining a quantitative answer. Dimensional analysis requires first, usually experimentally, to establish the physical quantities that intervene in the analyzed phenomenon. Then, applying either the Rayleigh method or the product method, the physical law is established based on the physical quantities that determine the considered phenomenon.

MethodsDimensional analysis model by the product method. The product method starts from the consideration that a dimensional quantity of the analyzed physical phenomenon, F, is a function of "n" dimensional quantities, denoted $a_1, a_2, ..., a_n$, of the form:

$$F = f(a_1, a_2, ..., a_n). \tag{1}$$

It is considered that the first k quantities ($k \leq n$) have independent dimensions, these being chosen as fundamental quantities. In this case, the dimensions of the dependent quantities $a_{k+1}, ..., a_n$ can be expressed in terms of the dimensions of the fundamental quantities $a_1, a_2, ..., a_k$.

The first stage of work on the product method consists in establishing the quantities that participate and influence the analyzed phenomenon. This stage is usually experimental.

The second stage consists in choosing the quantities that can be considered fundamental. As fundamental quantities can be chosen either the fundamental quantities of the system of measurement units in which one is working (usually the international system, IS), or a certain number of quantities that intervene in the studied phenomenon; in this second case, the fundamental quantities chosen must meet the following two conditions:

- to be independent from a dimensional point of view, that is, the size of a fundamental quantity cannot be obtained through a relation of the dimensions of the other fundamental quantities;
- the dimensions of the fundamental quantities allow the dimensional expression of all other derived (dependent) quantities.

The dimensions of the fundamental quantities $a_1, a_2, ..., a_k$ are noted as follows:

$$[a_1] = A_1,\ [a_2] = A_2,\ .....,\ [a_k] = A_k. \tag{2}$$

The dimensions of the quantities F, $a_{k+1}, ..., a_n$ will be expressed with the relations:

$$[F] = A_1^{m_1} \cdot A_2^{m_2} \cdot .... \cdot A_k^{m_k},\ [a_{k+1}] = A_1^{p_1} \cdot A_2^{p_2} \cdot .... \cdot A_k^{p_k},\ [a_n] = A_1^{q_1} \cdot A_2^{q_2} \cdots A_k^{q_k} \tag{3}$$

If the measurement units of the fundamental quantities are changed, for example they increase or decrease with $\alpha_1, \alpha_2, ..., \alpha_k$ times, then the numerical values of these quantities and of the quantities F, $a_{k+1}, ..., a_n$ in the new system of measurement units, will be:

$$\begin{array}{ll} a'_1 = \alpha_1 \cdot a_1 & F' = \alpha_1^{m_1} \cdot \alpha_2^{m_2} \cdot .... \cdot \alpha_k^{m_k} \cdot F \\ a'_2 = \alpha_2 \cdot a_2 & a'_{k+1} = \alpha_1^{p_1} \cdot \alpha_2^{p_2} \cdot .... \cdot \alpha_k^{p_k} \cdot a_{k+1} \\ .... & .... \\ a'_k = \alpha_k \cdot a_k & a'_n = \alpha_1^{q_1} \cdot \alpha_2^{q_2} \cdot .... \cdot \alpha_k^{q_k} \cdot a_n \end{array} \tag{4}$$

In the new system of measurement units we will have the expression:

$$\begin{aligned} F' &= \alpha_1^{m_1} \cdot \alpha_2^{m_2} \cdots \alpha_k^{m_k} \cdot F = \alpha_1^{m_1} \cdot \alpha_2^{m_2} \cdots \alpha_k^{m_k} \cdot f(a_1, a_2, ..., a_n) = \\ &= f(\alpha_1 a_1, ..., \alpha_k a_k, \alpha_1^{p_1} \cdot \alpha_2^{p_2} \cdots \alpha_k^{p_k} \cdot a_{k+1}, ..., \alpha_1^{q_1} \cdot \alpha_2^{q_2} \cdots \alpha_k^{q_k} \cdot a_n) \end{aligned} \tag{5}$$

The equality in relation (5) shows the fact that the function "f" is homogeneous in relation to the independent scale $\alpha_1, \alpha_2, ..., \alpha_k$ coefficients. The choice of these coefficients is made in such a way as to obtain the reduction of the number of arguments of the "f" function. A system of measurement units is chosen in such a way that the values of the first k arguments in the first part of relation (5) are equal to the unit, respectively of the form:

$$\alpha_1 = \frac{1}{a_1}, \alpha_2 = \frac{1}{a_2}, ..., \alpha_k = \frac{1}{a_k}. \quad (6)$$

For this system of measurement units, the numerical values of the F, $a_{k+1}, ..., a_n$ parameters are expressed by the relations:

$$\Pi = \frac{F}{a_1^{m_1} \cdot a_2^{m_2} \cdots a_k^{m_k}}, \Pi_1 = \frac{a_{k+1}}{a_1^{p_1} \cdot a_2^{p_2} \cdots a_k^{p_k}}, ..., \Pi_{n-k} = \frac{a_n}{a_1^{q_1} \cdot a_2^{q_2} \cdots a_k^{q_k}}. \quad (7)$$

It is easy to verify that the sizes $\Pi, \Pi_1, ..., \Pi_{n-k}$ are dimensionless.

The initial relationship $F = f(a_1, a_2, ..., a_k, a_{k+1}, ..., a_n)$ can also be written in the form:

$$\Pi = f(1, 1, ..., \Pi_1, ..., \Pi_{n-k}) = f_1(\Pi_1, \Pi_2, ..., \Pi_{n-k}). \quad (8)$$

In this way, the relationship between the "n+1" dimensional quantities F, $a_1, ..., a_n$, independent of the choice of the system of measurement units, can be written in the form of a relationship between "n+1-k" and $\Pi, \Pi_1, ..., \Pi_{n-k}$ dimensionless quantities. This result is also known as the π theorem or the product theorem.

Results

Following the experimental observations, they were considered as physical parameters that influence the propulsion force, the speed of movement, the distance over which the movement is made, the duration of time for the movement, the mass of the human subject and its age. The dependence function for the propulsion force can be written as follows:

$$F_p = f(v, d, \Delta t, m, age), \quad (9)$$

where: *v* – speed, d – travel distance, *Δt* – the time the movement takes, *m* – mass of the subject and age – age of the human subject.

The quantities *d, Δt* and *m* are chosen as fundamental quantities and the dimensionless products are constructed:

$$\Pi = \frac{F_p}{d^{q_1} \cdot \Delta t^{q_2} \cdot m^{q_3}}, \ \Pi_1 = \frac{v}{d^{r_1} \cdot \Delta t^{r_2} \cdot m^{r_3}}, \ \Pi_2 = \frac{age}{d^{w_1} \cdot \Delta t^{w_2} \cdot m^{w_3}} \quad (10)$$

The formula that establishes the functional link between the five dimensional physical quantities $F_p = f(\mathrm{v, d}, \Delta \mathrm{t, m, age})$ is reduced, thanks to the application of the product method, to a formula between dimensionless products:

$$\Pi = f_1(\Pi_1, \Pi_2). \quad (11)$$

We determine the exponents q_i, r_i and w_i, i = 1, 2, 3, from the condition that the products Π, Π_1, Π_2 are dimensionless.

For Π we get:

$$[\Pi] = \frac{M \cdot L \cdot T^{-2}}{L^{q_1} \cdot T^{q_2} \cdot M^{q_3}} = M^{1-q_3} \cdot L^{1-q_1} \cdot T^{-2-q_2} \quad (12)$$

In order to have the dimensionless size condition fulfilled, the exponents of the dimensions M, L and T must be equal to zero, respectively:

$$\begin{cases} 1-q_3=0 \\ 1-q_1=0 \\ -2-q_2=0 \end{cases} \Rightarrow \begin{cases} q_1=1 \\ q_2=-2. \\ q_3=1 \end{cases} \tag{13}$$

For Π_1 we get:

$$[\Pi_1]=\frac{M^0 \cdot L \cdot T^{-1}}{L^{r_1} \cdot T^{r_2} \cdot M^{r_3}}=L^{1-r_1} \cdot M^{-r_3} \cdot T^{-1-r_2}. \tag{14}$$

Imposing the condition of dimensionlessness, that the exponents of dimensions L, M and T be equal to zero, we obtain:

$$\begin{cases} 1-r_1=0 \\ -1-r_2=0 \\ -n_3=0 \end{cases} \Rightarrow \begin{cases} \mathrm{r}_1=1 \\ r_2=-1 \\ r_3=0 \end{cases} \tag{15}$$

For Π_2 we get:

$$[\Pi_2]=\frac{L^0 \cdot T \cdot M^0}{L^{w_1} \cdot T^{w_2} \cdot M^{w_3}}=L^{-w_1} \cdot T^{1-w_2} \cdot M^{-w_3}. \tag{16}$$

Imposing the condition of dimensionlessness, that the exponents of dimensions L, M and T be equal to zero, we obtain:

$$\begin{cases} -w_1=0 \\ 1-w_2=0 \\ -w_3=0 \end{cases} \Rightarrow \begin{cases} \mathrm{w}_1=0 \\ w_2=1 \\ w_3=0 \end{cases} \tag{17}$$

Using relation (11) we can obtain the analytical expression of the propulsion force, in the form:

$$F_p=\frac{d \cdot m}{\Delta t^2} \cdot f_1\left(\frac{v \cdot \Delta t}{d}, \frac{age}{\Delta t}\right). \tag{18}$$

It is observed that the function:

$$f_1(\frac{\mathrm{v} \cdot \Delta \mathrm{t}}{\mathrm{d}}, \frac{\mathrm{age}}{\Delta \mathrm{t}})$$

is dependent, in this case, only on the ratio $\frac{\mathrm{age}}{\Delta \mathrm{t}}$, because:

$$\frac{v \cdot \Delta t}{d}=\frac{v}{\frac{d}{\Delta t}}=\frac{v}{v}=1=const.$$

Under these conditions, relation (18) takes the form:

$$F_p=\frac{d \cdot m}{\Delta t^2} \cdot f_1\left(\frac{age}{\Delta t}\right). \tag{19}$$

For the numerical simulation, we considered a group of 10 subjects running over a distance of 60 meters, for which we have the values given in table 1.

Table 1

Experimental values

No.	*d* [m]	*Δt* [s]	*m* [kg]	*age* [years]	*age/Δt* [years/s]
1	60	10.12	74	23	2.272
2	60	9.95	68	22	2.211
3	60	10.63	81	24	2.257
4	60	10.08	70	21	2.083
5	60	10.54	73	23	2.182
6	60	9.91	69	20	2.018
7	60	10.91	76	35	3.208
8	60	11.73	80	41	3.495
9	60	12.05	79	45	3.734
10	60	13.12	83	50	3.810

With the help of numerical data, the *age = f (Δt)* graph can be drawn, figure 1.

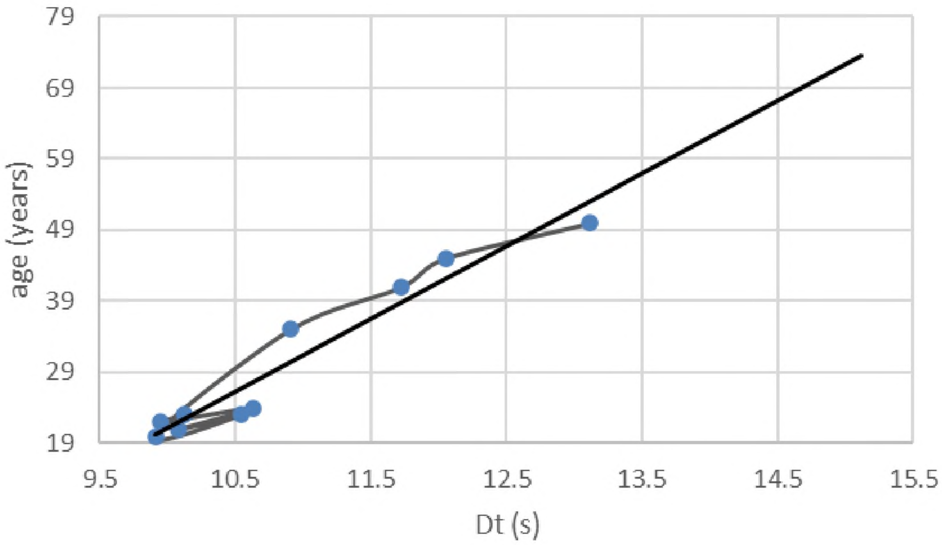

Figure 1. Dependence between *age* and *Δt*

The right, drawn in black in figure 1, which approximates the real curve, marked by dots, has the expression:

$$y = 10.217 \cdot x - 81.008, \quad (20)$$

where: $y = age$ and $x = \Delta t$.

The slope of this line is constant and represents precisely the f_1 function, it has a value of 10,217.

Under these conditions, relation (19) becomes, in this case, of the form:

$$F_p = 10.217 \cdot \frac{d \cdot m}{\Delta t^2}. \quad (21)$$

The values obtained for the propulsion force using relation (21) are given in table 2.

Table 2

Values for propulsion force

Nr. crt.	age [years]	m [kg]	Δt [s]	F_p [N]
1	20	69	9.91	430.701
2	21	70	10.08	422.329
3	22	68	9.95	421.053
4	23	74	10.12	442.940
5	23	73	10.54	402.824
6	24	81	10.63	439.433
7	35	76	10.91	391.416
8	41	80	11.73	356.425
9	45	79	12.05	333.524
10	50	83	13.12	295.586

Discussions and conclusions

From the analysis of the values calculated for the propulsive force, according to table 2, it is observed that as the age increases, the propulsive force decreases, the difference between the maximum and the minimum value being 33.2%. The graphic representation of the propulsion force depending on the subject's age is presented in figure 2.

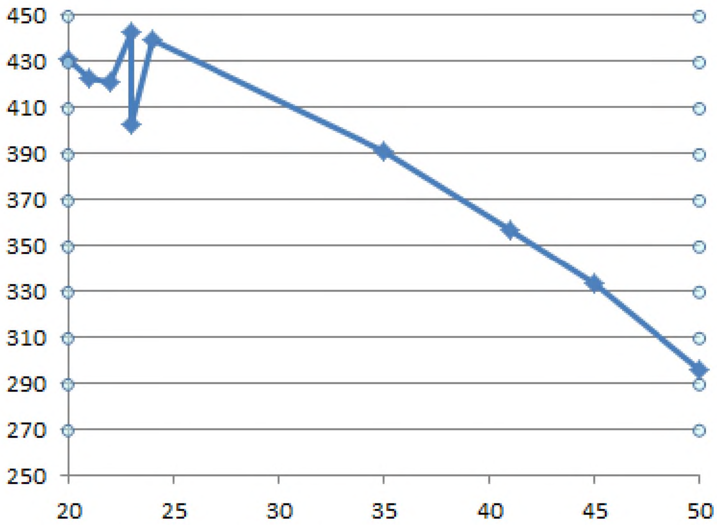

Figure 2. Dependence between F_p and *age*

Among the five physical parameters considered to influence the propulsion force, it can be observed that, in the end, only three of them have a direct influence (d, m, Δt) and the fourth *(age)* has an influence given by a constant through the given function by the ratio ($age/\Delta t$).

The greater the number of physical parameters, the closer the value of the analyzed physical quantity (the propulsion force, in this case) is to the real value. The most difficult stage of modeling through dimensional analysis is that of determining the function, denoted by f_1 in relation (11), as it is necessary to interpolate and write the equation of the interpolation curve.

Conclusion. The product method presented in this paper can also be used in the field of sports, when a physical quantity dependent on a number of experimentally observed physical parameters is desired to be expressed in a calculation expression.

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