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Krzysztof WIERZCHOLSKI*

TRIBOLOGY OF HUMAN METABOLISM BASED ON SKIN LUBRICATION

TRIBOLOGIA METABOLIZMU CZŁOWIEKA NA BAZIE SMAROWANIA SKÓRY

Key words: skin, sweat, underwear, sports clothing, lubrication, longevity, metabolic tribology, human metabolic age, training activity, sweat viscosity variations, experimental and analytical results.

Abstract: Human lifespan has been an exciting field and subject of many studies carried out by geriatric biomechanics specialists. They believe metabolic rather than chronological age determines healthy and active longevity. The issues of human Basal Metabolic Rate (BMR) and Metabolic Age (MA) form a new sub-domain of biotribology, where human health and limb function are indirectly related to the human living skin tissue lubricated with sweat during a motion of the inorganic surface of tight-fitting underwear (sports clothing). A biohydromechanic cooperation described this way significantly impacts a human's training activity, including but not limited to their limb function, and is finally related to human sweat's dynamic viscosity. In the summary, the article presents new biotribological studies to emphasise the complexity of direct and indirect synergistic impacts contributing to the change in the Basal Metabolic Rate and Metabolic Age values and their use in health science, sports and physiotherapy.

Słowa kluczowe: skóra, pot, bielizna, dresy, smarowanie, długowieczność, metaboliczna tribologia, wiek metaboliczny człowieka, aktywność treningowa, zmiany lepkości potu, doświadczalne i analityczne rezultaty.

Streszczenie: Długość życia człowieka bardzo ekscytowała i leżała w polu zainteresowań licznych biomechaników z dziedziny geriatrii. Według ich opinii, wyróżnikiem zdrowej i aktywnej długowieczności człowieka nie jest wiek chronologiczny, lecz metaboliczny. Problemy indeksu oraz wieku metabolicznego człowieka tworzą nową poddziedzinę naukowej dziedziny biotribologii, gdzie zdrowie i sprawność kończyn człowieka są pośrednio związane z żywą tkanką skóry człowieka smarowaną potem podczas ruchu nieorganicznej powierzchni ściśle dopasowanej bielizny (dresu). Tak opisana biohydromechaniczna kooperacja ma pokaźny wpływ na aktywność treningową człowieka, a w szczególności na funkcjonowanie jego kończyn; a w konsekwencji jest związana z lepkością dynamiczną potu człowieka. Praca w podsumowaniu przedstawia nowe badania biotribologiczne, aby uwidocznić złożoność pośrednich i bezpośrednich oddziaływań synergetycznych wpływających na zmiany wartości indeksu oraz wieku metabolicznego człowieka, a także na ich zastosowania w nauce o zdrowiu, oraz w sporcie i fizjoterapii.

STATE-OF-THE-ART

The current knowledge level of human Basal Metabolic Rate (BMR) and Metabolic Age(MA) is high for physiotherapy and sports medicine **[L. 1–5].** According to scientific research, human health depends primarily on such factors as internal (visceral) and external (subcutaneous) body fat, body mass index (BMI), total body weight, muscle and bone mass, percentage of water in the human body, the length of sleep, gender and eating habits. Nonetheless, experimental studies revealed that the impact of the abovementioned factors, accurately described through numerous formulas in scientific papers**[L. 6–8]**, does not always correspond to reality **[L. 9–16]**.This encouraged the author to explain and investigate the phenomenon of impact on a healthy human's lifespan using tribological methods. Such methods also apply to the influence of skin hydrodynamic lubrication with sweat on the BMR and MA synergistic effects.

* ORCID: 0000-0002-9074-4200. WSG University, Garbary 2 Street, 85-229 Bydgoszcz, Poland.

A thin coat of sweat is limited by the surface of the skin and underwear. The impact of sweat hydrodynamic lubrication on human health and fitness, depending on the mechanical properties of the skin and underwear/ sports clothing material, is noteworthy. They are characterised by high and low wettability of the interacting surfaces, related to hydrophobic and hydrophilic properties, and the modulus of elasticity of the skin tissue and underwear material (textile fabric). One shall not neglect the significance of such sweat ingredients as lactic acid (LA),power hydrogen ion concentration (pH), and urea water solution (UWS) and their properties.

PURPOSE

Previous research and scientific efforts within the sweat lubrication of the human skin's surface limited by underwear (sports clothing) were not related either to the Metabolic Age (MA) or the Basal Metabolic Rate (BMR). With regard to the above, the study's objectives are as follows:

Investigate and consider the impact of lubricating sweat flow characteristics – for the sweat occurring between the human skin and tight-fitting sports clothing (underwear) – on the increase in the Basal Metabolic Rate (BMR) and decrease in the Metabolic Age (MA),

Investigate and consider the impact of the material characteristics in tight-fitting sports clothing (underwear), including wettability, design and shape, responsible for the synergistic effects on the Basal Metabolic Rate,

Illustrate the impact of such sweat components as urea water solution (UWS), lactic acid (LA),and power hydrogen ion concentration (pH) on the values of the Basal Metabolic Rate and Metabolic Age.

SKIN, SWEAT AND CLOTHING LUBRICATION PHENOMENON

Scientific research in metabolic biotribology uses various kinematic and dynamic methods of sweat lubrication of human skin, limited by underwear, considering metabolic effects. **Figures 1a** and **b** show topological models of biotribology in the skin-sweat-underwear area, for interrelated studies. According to current knowledge, the presented research areas are completely new and have not been undertaken by any scientific centres in biotribology tissue engineering **[L. 1–2, 17–19]**.

a) b)

Fig. 1. Collection areas in metabolic tribology research; a) Conjunction of topological collections for the human skin – sweat – sports clothing (underwear) area, showing the tribological node's contact in the hydrodynamic lubrication issue, b) Augmentation of the sports clothing (underwear) – sweat – skin biological node during hydrodynamic lubrication implemented by sweat and heat flux expansion

Rys. 1. Obszary zbiorów występujące w badaniach metabolicznej tribologii: a) koniunkcja topologicznych zbiorów dla obszarów: skóra człowieka–pot–dres (bielizna) przedstawiająca kontakt węzła tribologicznego w problemie hydrodynamicznego smarowania, b) powiększenie węzła biologicznego dres (bielizna)- pot--skóra, podczas procesu hydrodynamicznego smarowania, implementowanego ekspansją potu i strumienia ciepła

MATERIALS, DEVICES AND ANALYTICAL TOOLS

The research area of hydrodynamic lubrication within the skin–sweat–underwear area is analysed for the human Basal Metabolic Rate (BMR) and Metabolic Age (MA) using living and non-living materials, anamneses, and electronic devices in measurements as well as biomechanics equations for numerical calculations.

Living materials were obtained in German scientific physiotherapy institutions during interviews, with students and patients doing general rehabilitation physical exercises, running and general strength measurements **[L. 11, 20]**. The non-living materials used in the tests included nylon, elastic, single-piece, tight-fitting sports clothing, ballet shoes and ballet slippers.

To complete the examinations, the following electronic devices were used: a Tanita MC 780MA Segmental Body Composition AnalyzerTanita, a Garmin Ltd.2015 pedometer, an IKA ROTAVISC lo-vi Complete Visco-meter, Mathcad 15 professional software, an Atomic Force Microscope (AFM) and a Scanning Microscope (ACM) **[L. 11, 21]**.

The theoretical random sweat lubrication issue is presented in 3D, using curvilinear orthogonal coordinates (a_i) for i = 1,2,3 by the following stochastic equations: equilibrium of momentum equations, a continuity equation, an energy equation and a Young-Kelvin Laplace equation[**L. 13, 22––23**]. Additionally, it uses constitutive equations with Navier Stocks equations. Elastic, hyper-elastic and bio-anisotropic deformations of the skin and clothing material are described by the equilibrium of momentum equations, physical dependencies, compatibility equations and a heat transfer equation. The expected values of the following unknown stochastic functions were determined **[L. 12]**: hydrodynamic pressure p [Pa], temperature T[K], human sweat velocity components v_i[m/s] for $i = 1, 2, 3$, dynamic sweat viscosity ηT (a_1, a_2,a_3) [Pas] and thegap $\varepsilon(a_1, a_3)$ [m] between the skin and clothing [**L. 7, 23**].

The dynamic viscosity of the human sweat depends on the sweat's dimensionless power hydrogen ion concentration p_H, hydrodynamic pressure p [Pa], sweat flow shear rate Θ [1/s], wettability *We* [grade] of the clothing material and the skin, and non-Newtonian properties manifested by sweat dimensionless flow index n, whereby (0.8<n<1.2). For n = 1, the Newtonian sweat flow applies. Furthermore, the dynamic sweat viscosity is a function of T[K] – temperature, $s = (N_A \cdot A)^{-1}$ [mol/m^2] – lactic acid concentration LA = [mg/100 ml sweat] molecules, A [m^2] − the region of lubricated skin surface coated by lactic acid (LA) molecules, N_A – Avogadro's number, C_K[g/l] – potassium, C_{Ca}[g/l] – calcium, C_{Na} [g/l] – sodium concentration in sweat [**L. 7**], TA – human training activity, E_d[Pa] – clothing material's modulus of elasticity, E_{skin}[Pa] – human skin's modulus of elasticity, ρ_{UWS} – calculated density of the urea water solution (UWS) [kg/m^3] in the sweat.

The UNR (Unit Net Region) mega algorithm was used to determine the Basal Metabolic Rate; the algorithm identifies the solutions for non-linear differential-recurrence equations **[L. 24]**. The boundary conditions were applied for hydrodynamic lubrication of human skin with sweat. Professional Matlab 7.3 and Mathcad 15 software were used in numerical calculations.

RANGES AND REGION-VALUE FOR SKIN-SWEAT-CLOTHING NODES

Human sweat consists mostly (90 per cent) of water, electrolytes, fatty acids, lactic acid, amino acids, carbohydrate nitrogen metabolites, such as ammonia, urea, uric acid, and urea water solutions (UWS) with the following density values: 1,084 kg/m^3<ρ_{UWS}<1,160 kg/m^3 for the temperature range between 293 K and 313 K. The values of the modulus of elasticity of the clothing material E_d and skin E_{skin} are 2 GPa<E_d<4 GPa and 0.02 GPa<E_{skin}<0.06 GPa. The hydrodynamic pressure p varies from 0.0014 MPa to 0.0017 MPa, and sweat velocity from 0.00 to 0.02 m/s. Moreover, the following values apply:N_A = 6.024·10^{23}, LA from 200 mg/100 ml to 400 mg/100 ml, pH = 4 – 7, and We = 40^o – 70^o. Sweat density at 293K ranges from 0.998 to 1.012 g/cm^3 **[L. 25]**. The value range of the typical human sweat's dynamic viscosity is between 1.21 and 4.414 mPas (cP). Male sweat contains more lactic acid (LA) than female sweat **[L. 25]**. Thus, laboratory measurement results demonstrate **[L. 25–26]** that power hydrogen ion concentration pH in male sweat is lower than in female sweat. Hence, considering the abovementioned remarks, male sweat's dynamic viscosity is higher than that of female sweat. The skin of a healthy human typically excretes (eliminates) ca. 1,200 ml of sweat daily and, additionally, 700 ml of sweat after intensive gymnastic training. A conventional Training Activity Effort (TA) unit scale was applied, with the scoring range TA = 1 – 5. One unit represents a sportsperson's effort while running over a 100 m distance at 2 m/s. Hence, unit level 5 denotes the effort made when running over a distance of 500 m at 2 m/s. The results are obtained for the following constant values of mineral concentration in sweat: C_{Na}= 0.85 g/l (sodium), C_K = 0.15 g/l (potassium), and C_{Ca} = 0.0015 g/l (calcium).

The numerical and experimental research used electromechanical devices, tools, and numerical software described in Subsection 4. Consequently, the value change ranges of the Basal Metabolic Rates (BMR) were obtained in kilocalories and of the Metabolic Age in years, as follows: 1Kcal<BMR<3 Kcal, and 0<MA<3.

In the hydrodynamic pressure, value increases and decreases in the geometric area of the skin-sweat-clothing tribological node. Mobile or immobile skin and clothing limiting the gap are filled with sweat. Sweat velocity distribution can be observed across the gap **[L. 27]**. Such a node is shown in **Fig. 2a, b,** and **c**.

The distribution of the sweat flow velocity across the gap, shown in **Fig. 2a**, is caused by the motion of the clothing surface at the immobile skin and by the increase in hydrodynamic pressure.

The sweat flow velocity distribution profile shown in **Fig. 2b** results from the clothing's surface motion in two opposite directions at the hydrodynamic pressure drop.

The sweat flow velocity distribution profile shown in **Fig. 2c** results from the clothing's surface motion in two opposite directions at the same hydrodynamic pressure distribution.

Sweat flow velocity distributions presented in **Fig. 2abc** result from Poiseuille's law **[L. 27–28]**.

DIRECT AND INDIRECT TRIBOLOGYINFLUENCES ON BMR AND MA INDEXES

Figure 3 illustrates direct and indirect parameters of impact on the human Basal Metabolic Rate (BMR) and Metabolic Age (MA) values **[L. 6, 10, 28]**. The presented results were obtained through experimental measurements followed by scientific analytical studies.

Moreover, **Figure 3** shows the impact of factors (parameters) that directly or indirectly change the sweat's dynamic viscosity.

SPORTS CLOTHING GEOMETRY TRENDS AND SYNERGISTIC COUNTERACTION

Figures 4a, b, c and **d** show manikins of sportspersons wearing single-piece tight-fitting nylon sports clothing, where additional synergistic interactions of forces and pressure were observed during training activity.

The forces marked in the drawings are perpendicular and tangent to the skin's surface. The occurrence of such synergistic effects was confirmed in anamnesis and measurements.

The tight-fitting, one-piece nylon clothing or underwear whose design and geometry are presented in **Fig. 4a, b, c**, and dprovide synergistic

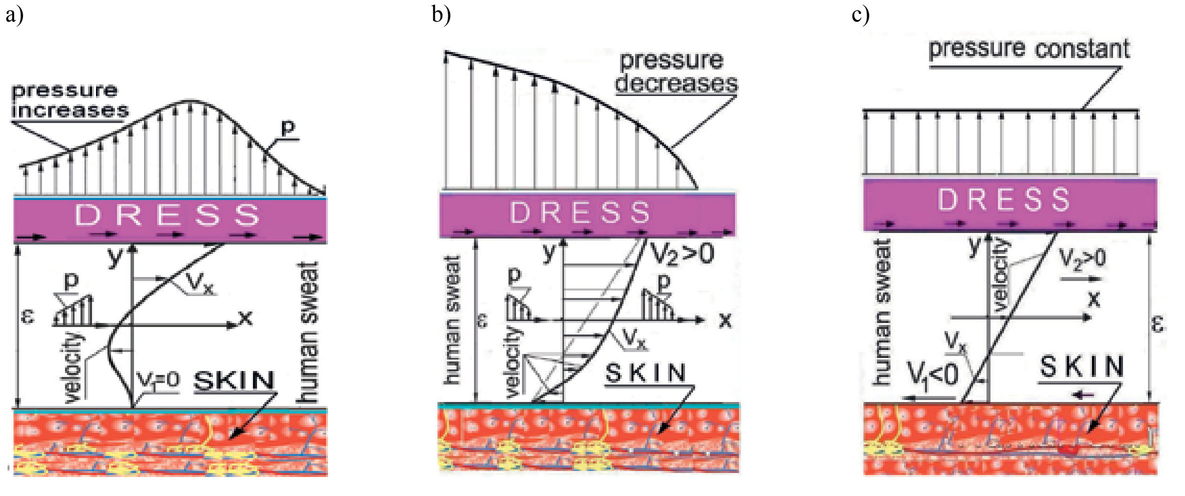

Fig. 2. Geometric areas of tribological nodes: a) Tribology of the clothing's mobile surface and human skin's immobile surface with the increase in the hydrodynamic pressure force effect perpendicularly to the tight-fitting clothing material, b) Tribology of the clothing's mobile surface and skin's mobile surface in the direction opposite to the clothing motion's direction, with the decrease in the hydrodynamic pressure forces effect perpendicularly to the tight-fitting clothing material, c) Tribology of the clothing's mobile surface and skin's mobile surface in the direction opposite to the clothing motion's direction with a constant load of the constant hydrodynamic pressure forces, perpendicularly to the tight-fitting clothing material

Rys. 2. Obszary geometryczne węzłów tribologicznych: a) tribologia obszaru ruchomego dresu oraz nieruchomej powierzchni skóry człowieka wraz ze wzrostem efektu sił hydrodynamicznego ciśnienia w kierunku prostopadłym do ściśle dopasowanego materiału dresu, b) tribologia obszaru ruchomego dresu oraz ruchomej powierzchni skóry w kierunku przeciwnym do ruchu dresu wraz ze spadkiem efektu sił hydrodynamicznego ciśnienia w kierunku prostopadłym do ściśle dopasowanego materiału dresu, c) tribologia obszaru ruchomego dresu oraz ruchomej powierzchni skóry w kierunku przeciwnym do ruchu dresu wraz ze stałym obciążeniem stałymi siłami ciśnienia hydrodynamicznego w kierunku prostopadłym do ściśle dopasowanego materiału dresu

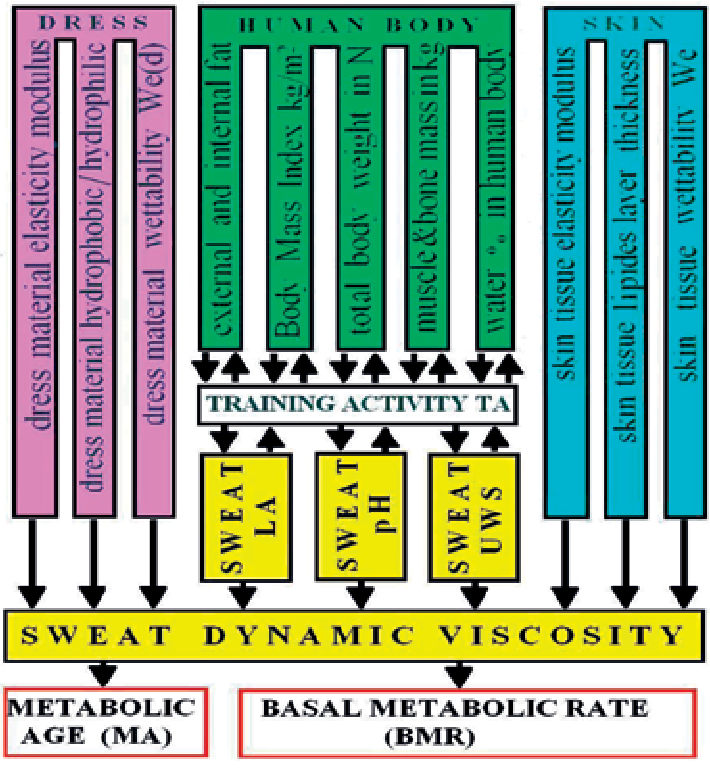

Fig. 3. Human Basal Metabolic Index (BMR) and Metabolic Age (MA) as a function of human sweat dynamic viscosity indirectly dependent on individual biological components of the human body (BMI, muscle, bone and fat mass) and directly dependent on the parameters of human skin lubrication with sweat, including lactic acid (LA), power hydrogen ion concentration (pH), and urea water solution (UWS), and additionally of the modulus of elasticity E_d,wettability We_d, tight-fitting material of the sports clothing and skin tissue's modulus of elasticity E_{skin}

Rys. 3. Podstawowy Indeks Metaboliczny (BMR) oraz Wiek Metaboliczny (MA) człowieka jako funkcja lepkości dynamicznej potu człowieka, zależnej pośrednio od własnych biologicznych składowych ciała człowieka HB (BMI, masa mięśni, kości, tłuszczu) oraz bezpośrednio uzależniona od parametrów smarowania skóry człowieka potem takich jak kwas mlekowy (LA), koncentracja jonów wodorowych (pH), roztwór wodnego mocznika (UWS) w pocie, dodatkowo od modułu sprężystości E_d,nasiąkliwości We_d obcisłego materiału dresu oraz od modułu sprężystości E_{skin} tkanki skóry

Fig. 4. a, b, c, and d: Synergistic effects observed on the thin surface of single-piece tight-fitting nylon sports clothing caused by hydrodynamic lubrication of human skin with sweat. The forces are generated and controlled as vertical and tangent forces uniformly distributed on the surfaces of human limbs and counteract external loads and responses to achieve adequate fitness increase in acrobatic feats

Rys. 4. a, b, c, d: Synergetyczne efekty widoczne na cienkiej powierzchni nylonu jednoczęściowego, ściśle dopasowanego dresu sportowego powodowane hydrodynamicznym smarowaniem skóry człowieka potem, tworzone i sterowane między innymi w postaci sił pionowych i stycznych równomiernie rozłożonych na powierzchniach kończyn człowieka, przeciwdziałających zewnętrznym obciążeniom i ich reakcjom, aby uzyskać stosowny wzrost sprawności w akrobatycznych wyczynach effects during training activity.This fact denotes that during human sweat lubrication, the skin's hydrodynamic counteraction forces and human biological forces create an overall effect more significant than the sum of the individual effects of any of them. Moreover, the Basal Metabolic Rate increments and Metabolic Age decrements achieved during human skin hydrodynamic lubrication and after biophysical efforts render an entirety greater than a mere sum of its parts.

The abovementioned synergistic forces were noticed and measured experimentally during the training activity (running). Then, the results were demonstrated theoretically by hydrodynamic lubrication equations and through numerical calculations using various software solutions described in Subsection 4.

Such synergistic forces have not been investigated in bio-tribology so far **[L. 3, 23, 29]**, so the authors want to show the result by quoting the following initial calculation.

Example

Measurements done using a Segmental Body Composition Analyzer for an eighteen-year-old woman rendered the results directly affecting the BMR and MA values. The results are as follows:

TA = 0, BMI = 27.99 kg/m^2, external body fat 29%, water in the human body 34%, internal body fat 14%, muscle mass 55 kg, and bone mass 5.5 kg **[L. 11]**. By virtue of calculations, the parameters (results) indirectly contributed to a 7% increase in the BMR and a 4% decrease in the MA.

The next step involved measuring – for the same subject and using the same SBCA device - the following parameters directly affecting the BMR and MA:

TA = 3, LA = 200 mg/100 ml, pH = 5, ρ_{UWS} = 1,100 kg/m^3, η = 1.50 mPas, We = 50^o, E_d = 3GPa, E_{skin} = 0.04 GPa, T = 293 K, Θ = 500/s. By virtue of calculations, the parameters directly contribute to a 3% increase in the BMR and a 2% decrease in the MA.

Nonetheless, when simultaneously measuring the impact of direct and indirect parameters on the BMR and MA values for the same female subject, by virtue of the developed calculation algorithm, a ca. 12% increase in the BMR is obtained rather than 7+3 = 10; the MA value's drop amounts to ca. 7 per cent rather than 4+2 = 6 per cent.

Note:

Statistical calculations for the measurement data obtained for thirty students on the SBCA device help determine synergistic increases in the BMR index values ranging from 2 to 4 per cent, and they enable demonstrating that the MA value decrease may range from 1 to 3 per cent.

INFLUENCES OF TRIBOLOGY PARAMETERS ON BMR&MA INDEXES

In this Subsection, the authors present selected parameters of hydrodynamic lubrication in the skin–sweat–underwear system. Then, the parameter values of interacting tribological surfaces are described in detail. The surfaces directly affect the Basal Metabolic Rate (BMR) and Metabolic Age (MA). Electromechanical devices and numerical software mentioned in Subsection 4 were used to determine the abovementioned parameters. Sweat dynamic viscosity was demonstrated to depend on the density of the urea water solution (UWS), lactic acid (LA), power hydrogen ion concentration (pH) and modulus of elasticity of the skin and underwear material. The dynamic viscosity of the sweat was measured with an **IKA ROTAVISC** viscosity meter. The measurement results were developed with statistical methods.

Sweat dynamic viscosity depending on urea water solution (UWS) density

Figure 5a shows the increase in dynamic viscosity of sweat containing urea water solution (UWS) as a function of UWS density rise. **Figure 5b** illustrates the growth in the quotient of urea water solution (UWS) dynamic viscosity and water viscosity in UWS solution as a function of UWS density increase **[L. 30]**. The graphs in both Figures apply to the flow shear rate of sweat and UWS solution mixture of Θ = 100/s and Θ = 500/s, including the adequate TA value for wettability We = 40^o, power hydrogen ion concentration pH = 5, constant value of lactic acid LA = 200 mg/100 ml in sweat, and elastic modulus of the clothing material E_d = 2 GPa. It can be noticed that the dynamic viscosity of sweat containing UWS decreases as the temperature rises and increases as the flow shear ratedrops. Such characteristics comply with the commonly known attributes of non-Newtonian fluid.

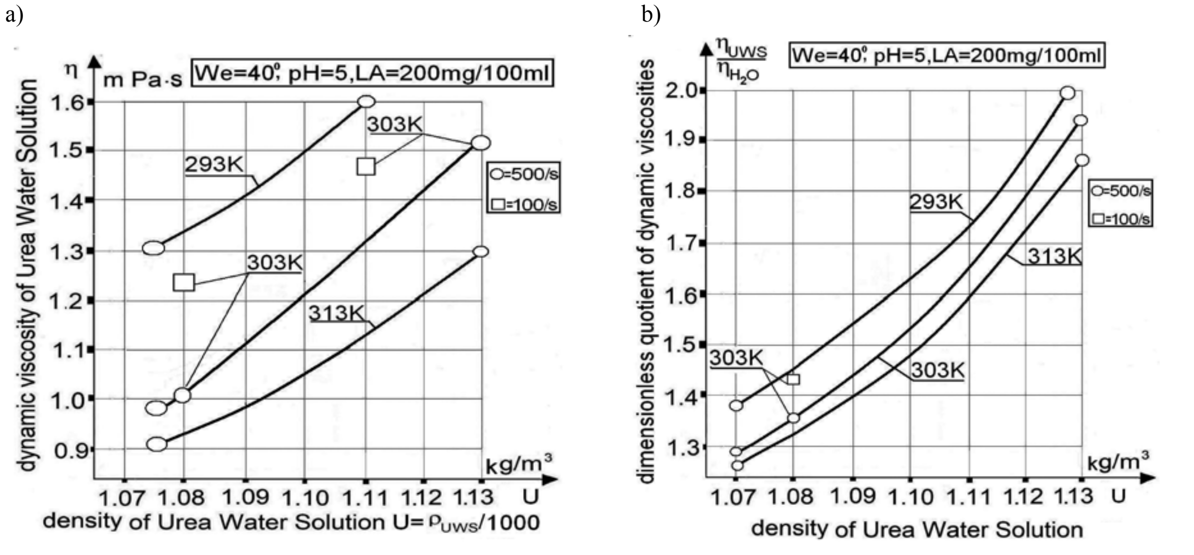

Fig. 5. Increase in the dynamic viscosity of sweat η [mPas] containing UWS as a function of UWS density from U = 1.08 kg/m³ to U = 1.13 kg/m³; a) increase in the dynamic viscosity of sweat containing UWS, b) increase in the dimensionless quotient of UWS dynamic viscosity and water dynamic viscosity. Symbols: Θ[1/s] – sweat flow shear rate, LA[mg/100 ml of sweat] – lactic acid index, T[K] = 293 K, 303 K, 313 K – sweat temperatures, We[°] – wettability of the underwear (sports clothing) material, pH – power hydrogen ion concentration, E_{skin}[GPa] – skin's modulus of elasticity, E_d [GPa] – underwear (sports clothing) material's modulus of elasticity

Rys. 5. Wzrost lepkości dynamicznej potu η [mPas] zawierającego UWS jako funkcja gęstości UWS od U = 1.08 kg/m³ do U = 1.13 kg/m³; a) wzrosty lepkości dynamicznej potu z dodatkiem UWS, b) wzrosty bezwymiarowego ilorazu lepkości dynamicznej UWS i lepkości dynamicznej wody. Oznaczenia: Θ[1/s] – wartość prędkości ścinania w przepływie potu, LA[mg/100 ml potu] – indeks wartości kwasu mlekowego, T[K] = 293 K, 303 K, 313 K – temperatury potu, We[⁰] – nasiąkliwość materiału bielizny (dresu), pH – potęgowa koncentracja jonów wodorowych, E_{skin}[GPa] – moduł sprężystości skóry, E_d [GPa] – moduł sprężystości materiału bielizny (dresu)

Sweat dynamic viscosity versus lactic acid (LA) index

Figure 6 shows the increase in sweat dynamic viscosity as the lactic acid content rises **[L. 7]**. The values were plotted in **Fig. 6**, considering two values of sweat flow shear rate Θ = 100/s and Θ = 500/s at the TA index rise and constant wettability value of We = 40°, at T = 303 K, for two UWS density values, i.e. U = 1.13 kg/m³ and U = 1.08 kg/m³, for power hydrogen ion concentration pH = 5, when the values of the sports clothing material's and skin's modulus of elasticity are as follows: E_d = 2 GPa and E_d = 4 GPa, E_{skin} = 0.05 GPa.

It is apparent that sweat dynamic viscosity increases as the UWS density value rises, which is confirmed by the result shown in **Fig. 5**. Moreover, sweat dynamic viscosity increases as the sports clothing material's modulus of elasticity increases. The rise in sweat dynamic viscosity as the sweat flow shear rate drops can also be observed. The results confirm the characteristic well-known properties of standard non-Newtonian fluids.

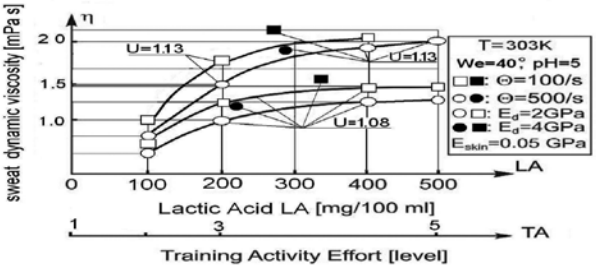

Fig. 6. Increase in the dynamic viscosity of sweat η [mPas] with the rise in lactic acid concentration from 100 to 500 mg/100ml of sweat for two dimensional values of the modified UWS density index U = 1.08 kg/m³, and U = 1.13 kg/m³. Symbols: Θ [1/s] - Θ [1/s] – sweat flow shear rate, T[K] – sweat temperature, We[°] – wettability of the underwear (sports clothing) material, pH – power hydrogen ion concentration, E_{skin} [GPa] – skin's modulus of elasticity, E_d [GPa] – underwear (sports clothing) material's modulus of elasticity

Rys. 6. Wzrost lepkości dynamicznej potu η [mPas] ze wzrostem kwasu mlekowego LA od 100 do 500 mg/100 ml potu, dla dwóch wymiarowych wartości zmodyfikowanego indeksu gęstości roztworu wodnego mocznika **U = 1.08 kg/m³, U = 1.13 kg/m³.** Oznaczenia: Θ[1/s] – wartość prędkości ścinania w przepływie potu, T[K] – temperatura potu, We[⁰] – nasiąkliwość materiału bielizny (dresu), pH – potęgowa koncentracja jonów wodorowych, E_{skin}[GPa] – moduł sprężystości skóry, E_d[GPa] – moduł sprężystości materiału bielizny (dresu)

Sweat dynamic viscosity versus power hydrogen ion concentration (pH)

Figure 7 shows a decrease in sweat dynamic viscosity as the power hydrogen ion concentration (pH) increases from 4 to 8 **[L. 7]**. The values were plotted in **Fig. 7** for two values of sweat flow shear rate Θ = 100/s and Θ = 500/s at the TA drops and constant wettability value of We = 40°, at constant T = 303 K, for a fixed lactic acid content LA = 200 mg/ 100 ml in sweat, at two UWS density values, i.e. U = 1.13 kg/m^3 and U = 1.08 kg/m^3, and for constant values of the sports clothing material's and skin's modulus of elasticity of E_d = 2 GPa and E_{skin} = 0.05 GPa.

It is apparent that sweat dynamic viscosity increases as the UWS density value rises, which is confirmed by the result shown in **Fig. 5** and **6**. Moreover, it can be observed that sweat dynamic viscosity rises as the sweat flow shear rate drops. The characteristics are typical for non-Newtonian fluids.

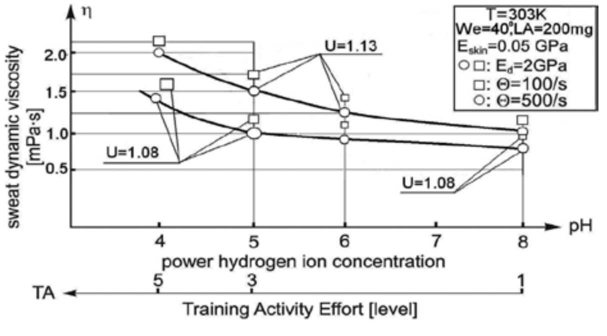

Fig. 7. Decrease in the dimensional sweat dynamic viscosity in [mPas] with power hydrogen ion concentration (pH)increased from 4 to 8. Symbols: Θ[1/s] – sweat flow shear rate, LA[mg/ 100 ml sweat] – lactic acid index, T [K] – sweat temperature, We[°] – wettability of the underwear (sports clothing) material, U[kg/m^3] – dimensional values of the modified UWS density index, E_{skin}[GPa] – skin's modulus of elasticity, E_d[GPa] – sports clothing's modulus of elasticity

Rys. 7. Spadek lepkości dynamicznej potu η [mPas] ze wzrostem bezwymiarowej wartości potęgowej koncentracji jonów wodorowych pH od 4 do 8. Oznaczenia: Θ[1/s] – wartość prędkości ścinania w przepływie potu, T[K] – temperatura potu, We[°] – nasiąkliwość materiału bielizny (dresu), LA[mg/100ml potu] indeks wartości kwasu mlekowego, E_{skin}[GPa] – moduł sprężystości skóry, E_d[GPa] – moduł sprężystości materiału bielizny (dresu)

HUMAN BASAL METABOLIC RATE AND METABOLIC AGE

The basal metabolic laws were applied to the equations of sweat hydrodynamic lubrication described in Subsection 4. Then, following numerical calculations and using experimental values of sweat dynamic viscosity shown in **Figures 5–7**, Subsection 8, comprehensive values of the Basal Metabolic Rate (BMR) and Metabolic Age (MA) were determined.

The results are illustrated graphically in **Figure 8.** An increase in the values of the human Basal Metabolic Rate (BMR)in Kcal and drops in the Metabolic Age (MA)in years can be observed for the Training Activity TA(η), related to the dynamic viscosity of sweatη, depending on the lactic acid (LA) content **[L. 7]**.

The BMR index is defined as the difference between the total daily energy used in Kcal and the energy expenditure during the daily human activity in Kcal. Hence, the BMR index can be said to denote how many calories one's body burns while at rest. The Department of Nutritional Sciences at the University of Connecticut estimated the following BMR values for human age groups: 20–29 years:1,360 calories; 30–49 years:1,300 calories; and 50–70 years: 1,200 calories.

The Metabolic Age (MA) indicates how many calories one's body burns at rest, compared to the average BMR for people of a certain chronological age in the general population. According to C.J. Anderson, the MA is commonly defined as how one's BMR compares to the average BMR for people of the same chronological age. The human MA is converted from calories to time in years after comparing one's BMR to the average chronological age group.

The success after a training activity denotes decreasing human MA values. The effect is positive (negative) when the MA is lower (higher) than the subject's actual chronological age **[L. 7]**.

The evaluated results presented in **Figure 8** are obtained for the same modified constant values of skin, sweat and clothing parameter data as those used in Subsections 5 and 8, i.e. C_{Na} = 0.85 g/l, C_K = 0.15 g/l, C_{Ca} = 0.0015 g/l, U = 1.08 kg/m^3, U = 1.13kg/m^3, E_d = 2 GPa, E_d = 4 GPa, and E_{skin} = 0.05 GPa.

The study results plotted in **Figure 8** reveal that the BMR values increase from 1 Kcal to 3 Kcal,

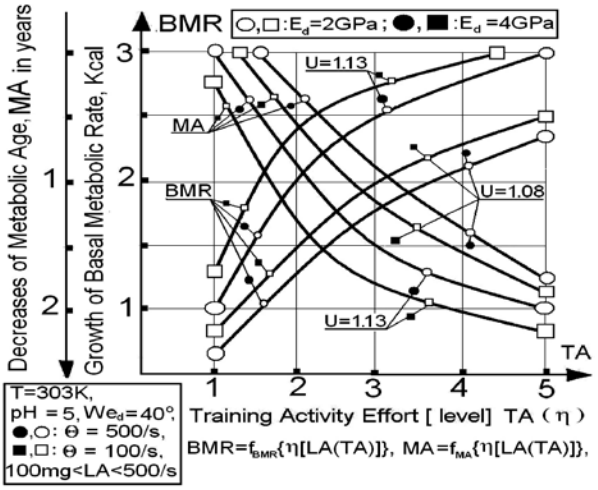

Fig. 8. Increase in the human Basal Metabolic Rate (BMR) from 1 to 3 Kcal and more significant drops in the human Metabolic Age (MA) in the 0–2 years range, as a function of value after completing a training activity (TA) (η) from 1 to 5, depending on the sweat dynamic viscosity described with the η(LA) function, depending on the lactic acid (LA) value in the 100 mg/100 ml – 500 mg/100 ml sweat range, for the following constant values: underwear (sports clothing) material surface wettability We = 40°, temperature T = 303 K, sweat flow shear rate Θ = 500/s and Θ = 100/s, power hydrogen ion concentration pH = 5, modified values of UWS density index U = 1.08 kg/m³ and U = 1.13 kg/m³, modulus of elasticity of the underwear (sports clothing) material E_d = 2GPa and E_d = 4GPa, and skin's modulus of elasticity E_{skin} = 0.05GPa

Rys. 8. Wzrosty Podstawowego Indeksu Metabolicznego (BMR) człowieka w przedziale od 1 do 3 Kcal oraz wzrosty spadku Wieku Metabolicznego człowieka (MA) w przedziale od 0 do 2 lat jako funkcja wartości po dokonanym wysiłku treningowej aktywności TA(η) od 1 do 5, zależnej od lepkości dynamicznej potu opisanej funkcją η(LA), zależną od wartości kwasu mlekowego w przedziale 100 mg/100 ml <LA <500 mg/100 ml potu dla następujących stałych wartości: nasiąkliwość powierzchni materiału bielizny (dresu) We = 40°, temperatura T = 303 K, prędkości ścinania przepływu potu Θ = 500/s &Θ = 100/s, koncentracja jonów wodorowych pH = 5, zmodyfikowane gęstości indeksu UWS wodnego roztworu moczu U = 1.08 kg/m³ & U = 1.13 kg/m³, moduły sprężystości materiału bielizny (dresu) E_d = 2 GPa & E_d = 4 GPa, oraz moduł sprężystości skóry E_{skin} = 0.05 GPa

while the MA decreases in the 3 to 0 years range for the following cases:

- If the sweat flow shear rate drops from Θ = 500/s to Θ = 100/s and when the training activity rises in the 1<TA<5 range.
- If in the successive training activities 1<TA<5,tight-fitting sports clothing is used with a gradually increasing material's modulus of elasticity in the 2GPa<E_d<4GPa range.
- If the UWS density in sweat rises in the 1.08 kg/m³<U<1.13 kg/m³ range, at the training activity increase1<TA<5.

Figure 8 shows that the BMR and MA are the functions of TA, i.e. BMR (TA), MA(TA), so they depend on the training activity. Training activity, in turn, is the function of sweat dynamic viscosity, which depends on lactic acid content, hence the TA[η(LA)] function relationship. This means that the BMR and MA are the lactic acid (LA) functions, i.e. BMR(LA), MA(LA).

Sweat dynamic viscosity depends not only on the lactic acid content (η(LA)) but also on such parameters as the human body weight in kg, BMI index in kg/m², external (subcutaneous) and internal (visceral) body fat in %, water content in the human body in %, bone mass in kg and muscle mass in kg.

Dynamic viscosity increments during the human skin lubrication imply the rising hydrodynamic pressure's impact. The pressure is recalculated into energy. Next, energy is converted into BMR calories using metabolic thermodynamics equations connected with the hydrodynamic energy equation, heat flux, and bio-metabolic equations **[L. 31–32]**. Hence, the BMR value increases.

CONCLUSIONS

This paper presents some new scientific bio-tribology achievements in the field of human skin lubrication related to the metabolic effects in the human body and limb efficiency linked to the Basal Metabolic Rate (BMR) and Metabolic Age(MA).

1. The increments of the human Basal Metabolic Rate and more significant drops of human Metabolic Age (MA) indirectly depend on sweat dynamic viscosity and rise after training activity.
2. If the sweat shear rate decreases and the training activity increases, then the human BMR values rise, and the human Metabolic Age (MA) drops.
3. If the elastic modulus of the clothing (underwear) material increases, and it happens after training activity, then the human BMR values increase, while the human Metabolic Age (MA) decreases.

4. If the modified dimensional density of urea water solution in the sweat increases, and it happens after training activity, then the human BMR values increase, and the human Metabolic Age (MA) decreases.
5. Apart from new research, tendencies in the human skin-sweat lubrication illustrate synergistic problems in relation to the sweat-clothing lubrication phenomena for the human skin and clothing across the very thin boundary sweat layer:
   - Due to many initial calculations, it is evident that by virtue of synergistic effects, we can anticipate the total BMR value indexto increase from about 2 to 4 per cent and an MA value to decrease from about 1 to 3 per cent.
   - During the training activity in a one-piece tight-fitting clothing, additional synergistic tangential and standard forces impact the sportsperson's skin, body surface and limbs. The forces are uniformly distributed all over the body surface and reach proper efficiency and efficacy increments for acrobatic feats, which can lead to the subject's reduced Metabolic Age.

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DISCUSSION

BMR is also known as the Resting Metabolic Rate (RMR). Nevertheless, the exact number of calories consumed at rest is represented by the Resting Energy Expenditure (REE) index. The BMR and REE values are calculated differently; the difference amounts to ca. 10 per cent. According to the Department of Nutritional Sciences at the University of Connecticut, the value of 1,800 calories is relevant, as the BMR depends on several factors, including age, gender, weight, and the level of physical activity. The BMR index can vary individually, and there is no single correct BMR value. Typically, the BMR of 1,800 calories is considered to be within the normal range for an adult female of an average height and weight who engages in physical activity. However, according to the literature, the BMR value is only a factor determining the needed daily intake of calories but the physical activity level should also be considered.

In this paper, the authors have proven that human sweat dynamic viscosity variations during skin-clothing hydrodynamic lubrication contribute to the increasing BMR and decreasing MA values. Why is this phenomenon valid? It is evident that dynamic viscosity causes a hydrodynamic pressure increase during human skin dynamic lubrication with sweat. Hence, energy and fat increase calorie burning by enhancing the breakdown of fat cells. The additionally obtained energy is converted into calories, systematically improving BMR values. To calculate the BMR value, we can use the following formulae well-known in literature, e.g., Harris-Benedict, Mifflin-St.Jeor, Katch-McArdleor the Cunningham Equation calculator. Unfortunately, we seldom obtain the same BMR value using the formulae above for the same person. According to the authors' suggestion, the differences result from the fact that the referenced formulae do not consider skin lubrication influences caused by different sweat dynamic viscosity values and synergistic effects. To the best of the authors' knowledge, the impact of sweat dynamic viscosity on BMR and MA values is significant because the entire skin surface of a sound human typically excretes (eliminates) ca. 1,200 ml sweat daily and additionally 800 ml sweat after intensive physical activity. Drinking coffee contributes to higher sweat dynamic viscosity, and caffeine can boost metabolism. Studies have shown that caffeine can increase the amount of energy consumed, and thus, the RMR value can rise by up to 11 per cent.

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