TOPICS IN EXERCISE SCIENCE AND KINESIOLOGY

Review

Exploring the Mechanistic Trail Connecting Cellular Function, Health, and Athletic Performance with Phase Angle: A Narrative Review on the Physiology of Phase Angle and Exercise-Based Interventions

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ABSTRACT

Topics in Exercise Science and Kinesiology Volume 5: Issue 1, Article 7, 2024. Bioelectrical impedance analysis-derived phase angle (PhA) has been widely used in clinical and sports settings, as it is positively associated with health and fitness. However, what PhA is measuring at the cellular level has not been addressed, which limits our interpretation of PhA. The purpose of this review is to provide a roadmap, starting with the mechanistic link between the dielectric properties of mammalian cells and their physiological function. In simplistic terms, PhA measures cellular permittivity and electrical conductivity. These characteristics determine cellular health and function. This theory is the crux of how PhA relates to physiological function. One of the foundational assumptions is that PhA is affected by cellular membrane integrity. Intact cell membranes are essential for proper cellular function, namely cell-to-cell communication and intracellular signaling. This also relates to the quality of neuromuscular communication, or the ability of the neural system to control motor output, which accounts for the increased PhA values after exercise training. This paper summarizes the most recent reports of PhA in relation to exercise training and status, disease, age, and sex. Also, we offer future avenues of research that will help to understand how to best utilize and interpret PhA. By matching the relevant background information about cellular changes that occur with health or disease to PhA values, researchers and clinicians will better understand the assumptions when using bioelectrical impedance-derived PhA. Overall, this review provides practitioners with insight into what changes in PhA could mean in terms of cellular health and function.

KEY WORDS: Bioelectrical Impedance Analysis, training, performance, health, disease, age

INTRODUCTION

Phase angle (PhA) has been widely used in both clinical and sports settings to measure health and performance (24, 72, 87). The majority of these research studies have only reported PhA values while neglecting to report the other bioimpedance analysis (BIA)-derived variables that determine PhA. These variables are the raw values from which PhA is derived and are just as important to consider as the resultant PhA. Therefore, the objective of this review is to describe the potential cellular mechanisms that alter the raw BIA values that may account for improvements in PhA after exercise training. Then, by combining these underlying mechanisms with the adaptations of the neuromotor system to exercise training, we can better understand and appreciate the effect of training on PhA. With this enhanced understanding, as a scientific community, we will be better equipped to develop pointed research questions and use resultant raw BIA values to make educated guesses about what may be happening on a cellular level. By providing relevant background information about what PhA is measuring, researchers and clinicians will be better able to interpret BIA-derived PhA when using it as an index of cellular health.

It should be noted that BIA is affected by hydration status (77,111) and historically, this relates to the measurement of body composition. However, with the measurement of PhA, if measured under the same conditions and using appropriate pre-testing guidelines to ensure consistent testing procedures, comparison of PhA across multiple time points is possible. We refer readers to previous research which documents the reliance of BIA on hydration status, fluid compartment shifts (upright posture with gravity causes fluid accumulation in the lower body whereas a supine posture causes fluid to redistribute evenly across the body), and an overview of BIA technologies (77). There has been an abundance of PhA research showing its relationship to health in individuals with diseases across a large spectrum including HIV (80), anorexia (57), Crohn's disease (82), and cardiovascular disease (112). In these disease states, fluid compartments have been perturbed, i.e., dehydration with anorexia, fluid shift to lower limbs with cardiovascular disease. Patients with type II diabetes (44) may have a disease-triggered thirst and could putatively have greater hydration. Among these different disease states, PhA has consistently been shown to be reduced with disease, regardless of hydration or fluid shifts. These phenomena could be related to hydration status, or more likely, also related to other cellular mechanisms. In this paper, we provide possible underlying mechanisms that could explain the reduction in PhA (PhA seemingly always goes in one direction, down, despite fluctuations in hydration/fluid compartment shifts). Then, by reverse-engineering the gathered evidence, we offer insight into ways to improve PhA in clinical and sports settings.

The first section of the paper describes the cellular and electrical properties of mammalian tissues and outlines the mechanistic trail that connects cellular function and PhA. The next section describes how these cellular characteristics relate to PhA. In the second half of the paper, we summarize reported PhA values concerning exercise training and fitness status, disease, age, and sex and illustrate the connection between the possible cellular mechanisms and clinical findings. We conclude by presenting our current understanding of the effect of exercise interventions on PhA. Throughout the manuscript, we highlight different research avenues that could help to understand how PhA can be applied in sports and clinical settings, specifically focusing on how exercise could be used to positively influence PhA and cellular health.

METHODS

Protocol

The present review utilized a literature search to locate relevant research articles that describe the physiology of PhA, and the efficacy of exercise interventions to alter PhA. To our knowledge, cellular electrophysiology mechanisms have not been used to explain resultant PhA measurements. Therefore, the papers included in this review were selected because they helped to explain the cellular mechanisms that could describe what PhA is measuring on a cellular and subcellular level. Electronic databases (PubMed and Google Scholar) were used to perform the literature searches with various combinations of search terms, including "*phase angle, bioelectrical impedance analysis, reactance, resistance, electrophysiology, cellular membrane integrity, physiological milieu, health, sport performance*," and "*effect of exercise*." Manuscripts included in the present study were required to be written in English, in full-text versions, and derived from peer-reviewed journals including study designs such as narrative reviews, systematic reviews, meta-analysis, randomized control trials, quasi-experimental methods, and mixed-methods. Databases were searched from November to August of 2023. To further identify relevant research, references of all full-text articles were utilized. Manuscripts were excluded from analysis if a full-text version was not available, and if not written in English. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science (71).

ELECTROPHYSIOLOGY

Cell Membrane Properties

The study of the dielectric properties of mammalian tissues and the respective tissue interactions with electromagnetic energy has allowed researchers to understand the biochemical and physiological characteristics of cells (84). The term dielectric describes the ability of the tissue to be polarized with electrical conduction, for example, cellular membrane polarization. The relative permittivity and electrical conductivity of tissues determine the dielectric properties of cells (84). Permittivity describes the level of opposition of the tissue against an electric field, where the higher the value, the greater the opposition against an electric field (i.e., air and water have a permittivity of 1.0 and 2.0, respectively.) For example, the permittivity of breast cancer cells is greater than the permittivity of healthy cells when under the influence of an electric field (68). This finding was one of the first observations that showed that healthy and unhealthy cells have different dielectric properties (68). Maintaining dynamic bioelectric properties is essential for housekeeping function and the integrity of cells as it is essential for trafficking (81, 87). For example, nutrients, metabolites, and ions must be transported across the hydrophobic cell membrane and this depends upon membrane-bound transporter proteins which rely on dynamic membrane potential (88). Cell excitability is a fundamental property of many cells, which allows a response to stimulation by changing membrane potential, where the potential is produced by asymmetric ion concentrations between the intracellular and extracellular space. In essence, the opening and closing of ionic channels leads to changes in membrane potential as intracellular and extracellular ionic concentrations fluctuate, which essentially describes action potential propagation.

In neurons, action potentials are integral for cell-to-cell communication, as the propagation of electrical signals along the axon can connect with other neurons, motor cells, or glands at the axon's terminal. In other types of cells, the main function of an action potential is to activate intracellular processes. For example, an action potential in muscle cells is the first of many steps toward a contraction, whereas, in beta cells of the pancreas, an action potential can provoke the release of insulin (92).

A cell's dynamic membrane potential plays a critical role in processes beyond the action potential, where for example, it mediates the cell cycle, cell-volume control, proliferation, muscle contraction, wound healing, secretion, and circadian rhythm (1). Many cell types are considered to have excitable cell membranes, including but not limited to neurons, myocytes (cardiac, skeletal, smooth), vascular endothelial cells, pericytes, juxtaglomerular cells, interstitial cells of Cajal, epithelial cells, enteroendocrine cells, pulmonary neuroendocrine cells, pinealocytes, glial cells, mechanoreceptor cells, chemoreceptor cells, and immune cells (23). The main constituents of a mammalian cell's dielectric properties include amino acids, proteins, electrolytes, and cell membranes (84). At the minimum, alterations to a cell's bioelectric constituents may affect dynamic resting membrane potential, cell integrity, and the excitability of a cell, which is likely to have a negative influence on neuronal communication and neuromotor output. On a larger level, the dielectric properties of individual cells affect systemic function, where alterations in membrane potential can impact cell growth, the cell cycle, and the function of all major systems and organs. Needless to say, detecting changes in membrane potential relates to intracellular processes, which have direct health implications in clinical and sports settings.

Phase Angle

BIA is a popular, safe, portable, non-invasive, and reproducible method that measures the bioelectrical characteristics of the human body (68). BIA is based on Ohms law, which states that $V = I * Z$, where V is voltage, I is current, and Z is impedance. Current flow throughout the body lags behind voltage due to the resistant properties of cell membranes and the physiological milieu within the body's tissues. Therefore, knowledge of the amount of current applied and the measurement of the subsequent voltage generated and lag effect allows for the calculation of bioelectrical impedance (Z) (7). Methods of BIA include single-frequency BIA, multi-frequency BIA, bioelectrical spectroscopy, segmental BIA, localized BIA, and vector BIA (37). Multi-frequency and multi-segmental BIA allows for the prediction of total body water, intracellular water, and extracellular water (36, 44). Based on an individual's height and an individual's resistance to an electrical current, BIA predicts body composition, including fat-free mass, fat mass, and body cell mass (36, 44). Recently, the use of raw measurements derived from BIA, such as PhA, has increased in popularity due to its significant relationship with markers of health and ease of use.

The following paragraph provides an overall picture of how Z is related to opposition to electrical flow and how these physical measures are related to cellular health and function. In the subsequent paragraphs, we summarize the factors that influence Z. Z is the opposition to electrical flow, which is a result of the interaction of two factors: resistance (R) and reactance (Xc). R is considered a passive resistant characteristic and does not change at different frequencies. R is primarily related to the amount of water and composition of the physiological milieu within the body's tissues (36, 87). In contrast, Xc is considered a reactive characteristic, and changes with altered frequencies. Xc is produced by cell membranes which act as capacitors and delay the electrical current (30, 87, 91).

PhA represents the geometric angle formed between R and Xc (Figure 1) and can be calculated as:

$$PhA = arctangent\ (\frac{Xc}{R}) \times (\frac{180°}{\pi})$$

Low PhA values indicate a reduction of cellular integrity and poor function and are represented by a low Xc and high R (31). High PhA values are associated with cellular health and intact cell membranes, which are presented as a high Xc and low R (98). PhA is affected by changes in cell membrane permeability, thus, PhA is considered an index of cellular membrane integrity (69, 72, 87).

PhA is also affected by changes in the capacitive behavior of the tissues, cell size and mass, and intracellular composition (24, 72, 78). Therefore, PhA is also considered an index of the ratio between intracellular water and extracellular water, and body cell mass (25). PhA should not be considered a diagnostic tool, but since it is a predictor of mortality, it could be used as a "temperature check" in terms of providing a general health status rating (52, 104). Existing empirical evidence suggests that exercise training (and improved fitness) induces increased Xc, decreased R, and PhA improvement, with the opposite effects occurring after detraining (Figure 1.).

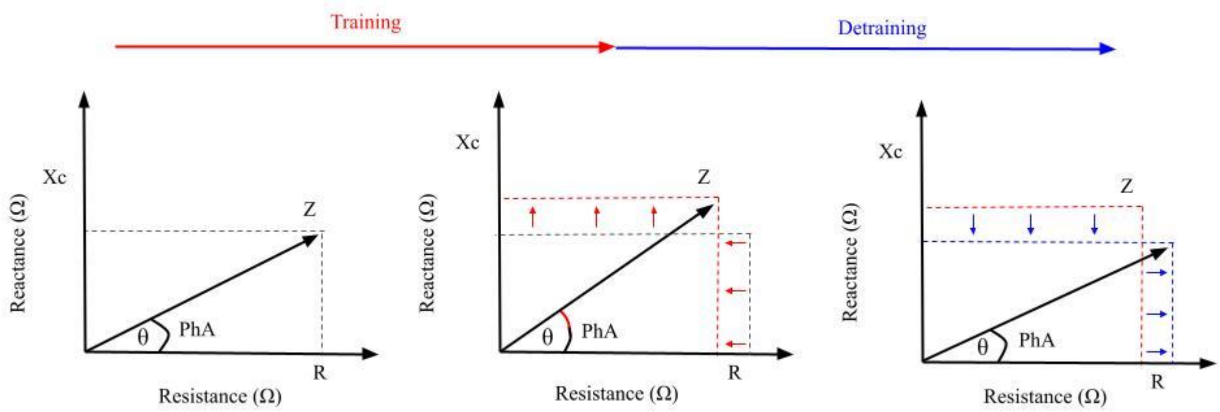

Figure 1. Theoretical effects of training and detraining on phase angle (PhA), Impedance (Z), reactance (Xc), and resistance (R) based on existing empirical evidence. Theta (θ) represents PhA, which is calculated as: arctangent (Xc/R) x (180°/π). The effect of training is depicted by the red arrows, showing an increased Xc, and decreased R, which increases phase angle (PhA). In contrast, detraining is depicted by the blue arrows, where there is a decreased Xc, increased R, which results in a decreased PhA.

Reactance (Xc) and Cellular Membrane Integrity

Cellular membrane integrity is of particular interest when considering the efficacy of exercise-based interventions in improving Xc and PhA. Cellular membranes are critical for cellular health as they separate intracellular and extracellular environments, create a barrier that controls the movements of substances in and out of cells (i.e., nutrients, and metabolic waste), and provide a platform for intracellular signaling (that directs gene signaling, mitochondrial function)(29). The function of cell membranes is typically reflected in the relative composition of lipids and protein, where the amount of protein is nearly equal to or greater than that of the lipids (84). Cellular membrane integrity reflects the ability to resist breaches and the repair capacity of the membrane; and can be assessed by the entry of cell-impermeable molecules, calcium influx, and intracellular events in extracellular space (4).

Cellular membrane damage can occur from mechanical, chemical, microbial, immune, and intracellular pathways (4). Cellular membrane damage, specifically membrane tears, can occur during muscular contraction and locomotion due to mechanical stress (4). During muscular contraction, myocytes buffer mechanical stress by stabilizing plasma membranes through the dystrophin-glycoprotein complex, and an abundance of caveolae (4), a specific type of lipid raft that is important for signal transduction, mechanoprotection, and mechanosensation (54). Caveolae is a structural component of the cell membrane and constitutes more than 50% of the sarcolemma of skeletal muscle (54). Muscle cells have an abundance of caveolae to buffer frequent mechanical stress, and specifically, they assist with the eccentric stretch of the plasma membrane and prevent membrane ruptures (19, 51). A decrease in caveolae can diminish the membrane's buffering capacity of mechanical stress, which could ultimately lead to more ruptures (54).

Furthermore, caveolae join the sarcolemma to t-tubules; caveolae have a direct relationship with action potential depolarization and subsequent calcium release (54). Eccentric muscular contraction can lead to physical breaches of the cellular membrane, which leads to a rise in intracellular calcium, as extracellular calcium enters the cell through the breach (4). Minor damage to the sarcolemma will disrupt calcium's role in muscular contraction, but this is a reversible injury (4). However, damage caused by excessive eccentric contractions can severely overwhelm calcium pumps, elevating intracellular calcium to dangerously high levels (4). The elevation of intracellular calcium levels can lead to the degradation of structural and contractile proteins and the phospholipids that comprise the sarcolemmal membrane (6). Still, muscular contractions, specifically eccentric contractions followed by adequate rest, provide a significant stimulus to muscle cell membranes, which may induce positive adaptations in membrane integrity after repair.

Cellular membrane repair is an essential component of healthy cellular function. After a cellular membrane breaches, the resulting influx of calcium serves as an ionotropic alarm that initiates membrane repair (4). Interestingly, cells have a "memory" of damaging events, enhancing repair upon subsequent injury (4). Physiological adaptations occur in response to mechanical stress and breaches of the muscle cell membrane, which improve the ability of the muscle cell membrane to resist breaches from future stressors (99). High-intensity interval training and continuous moderate exercise in rats increased the endothelial luminal caveolae density by 65% and 27%, respectively, whereas the levels of caveolin-1 (an isoform of the structural component of caveolae), increased by approximately two-fold in both training groups (38). Furthermore, another study showed that combining aerobic and resistance training was effective in improving endothelial progenitor cell function through upregulation of caveolin-1 in mice with type 2 diabetes (113). Thus, exercise-based interventions may increase levels of caveolae, which could improve cell membrane integrity as detected by an increased Xc, and augmented PhA.

However, it is unclear whether continuous endurance training, high-intensity training, or resistance training would be the optimal stimulus for increasing Xc and PhA. Based on the evidence provided, it is plausible that resistance training, specifically strength training and high-intensity training followed by adequate rest, may be a superior stimulus for improving PhA due to the high volume and magnitude of eccentric contraction utilized in this type of training. It is important to note that periodizing eccentric contractions would be important not to tip the myocytes into unfavorable cellular conditions, but rather provide sufficient stress to stimulate cellular recovery, repair, and growth. Additional research is needed to explore the effects of different training types on PhA. Furthermore, research is needed to explore the effects of muscular contraction type (eccentric, concentric, and isometric) on Xc and PhA.

Resistance (R) and Physiological Milieu

Optimal cellular function within the human body is maintained by the proper concentration of nutrients, ions, and essential constituents. The cells of the human body are bathed by a physiological milieu, which is kept constant and stable by numerous physiological processes. The R provided to alternating electrical current during BIA arises from the water and electrolytes in the intracellular and extracellular fluids of the body (49). During exercise, fluid homeostasis is challenged as body water is redistributed by fluid shifts between interstitial and vascular compartments, and as fluid moves between intracellular compartments and extracellular compartments (28). During endurance exercise, body water and electrolytes are lost due to thermoregulatory sweating, which evokes reflexes that restore the physiological milieu (28). To maintain circulatory homeostasis, the body closely regulates blood volume. Increases in plasma volume, or exercise-induced hypervolemia, is a hallmark adaptation of endurance training that enhances exercise performance (28).

It is estimated that ~60% of human tissue is water, with the majority being intracellular (45). The extracellular fluid volume contains intravascular and extravascular compartments. The regulation of plasma volume via hemodynamic shifts in fluids between compartments is critical to health and performance, as disproportionate fluctuations can result in hemodilution or hemoconcentration (45). Exercise-induced dehydration can reduce plasma volume, resulting in hemoconcentration and polycythemia, which causes the blood to be more viscous and increases stress on the cardiovascular system (95). Plasma volume expansion as a result of endurance training improves performance by increasing stroke volume, and countering the effects of exercise-induced dehydration (42). Exercise training results in an increase in total body water and an expansion of both intracellular and extracellular fluid compartments (28).

With dehydration, plasma volume and intracellular fluid may be reduced, increasing R and potentially causing a reduction in PhA. Also, isotonic hypohydration, in the case of bed rest or microgravity, in the absence of exercise would putatively lead to a reduced PhA as reduced total body water would increase R. Thus, in studies that measured PhA in a diseased state, whether the bedrest and resultant loss of plasma volume or the actual disease caused the reduction in PhA is to be determined. In terms of exercise in the absence of dehydration, the increased blood flow to skeletal muscles could act oppositely, causing a reduction in R and, an increase in Xc, and thus causing an acute increase in PhA. Still, it is important to consider that aerobic metabolism produces water (85), so the actual acute effect of exercise of varying intensities on PhA remains to be determined.

Furthermore, PhA has a moderate positive relationship with albumin (86), a protein involved in exercise-induced plasma volume expansion (21). Thus, adaptations from endurance-based exercise interventions may reduce R to electrical flow (25). Based on the information presented, it is plausible that resistance training may increase PhA by increasing Xc, whereas endurance training may increase PhA by decreasing R. Although, the large blood pressures observed during high-intensity resistance training result in hemodynamic shifts that may also influence R. Research is needed to confirm or refute these hypotheses. Future research should also explore the longitudinal and chronic effects of modalities that may result in fluid shifts, such as foam rolling, pneumatic compression, and percussion massage on PhA.

EXPECTED PHASE ANGLE VALUES IN DIFFERENT POPULATIONS

PhA values share a similar progression throughout the life cycle in both sexes, starting with relatively low values for infants 0–2 years old (~3.6°), then increasing progressively until the teenage years (16–18 years old; ~7.0–7.5°), stabilizes during adult ages (18–48 years old), and then progressively declines in elderly individuals (80 years old; ~5.4°) (67). Although the pattern of PhA throughout the life cycle is similar between sexes, PhA values in males are generally higher in all age groups except in infants (67).

Reference values in sports indicate that endurance athletes have lower PhA values when compared to velocity/power-based or dynamic intermittent team sport athletes (16). Differences in PhA values between athletes and non-athletes have been shown in males, but not females, potentially showing sex differences in PhA responsiveness (100). However, these results are from one study, so these results should not be interpreted as conclusive evidence. Still, healthy females have lower PhA values than age-matched healthy males (9, 16, 64), which suggests that the magnitude of PhA improvement in females would be smaller and would require more statistical power to detect significant changes. Additionally, the phase of the menstrual cycle may affect PhA as water retention is commonly observed, which could putatively decrease R, and increase PhA. However, the effect of the menstrual cycle on PhA remains controversial and is yet to be determined (22,48). In conclusion, empirical evidence suggests that PhA values are higher in athletes and active individuals than in sedentary controls (25), stating that exercise interventions are capable of promoting increased PhA. Furthermore, relative changes in the PhA of bodybuilders compared to endurance athletes (cyclists and marathon runners) suggest that muscle strengthening may induce greater increases in PhA compared to endurance training (25). However, it remains unclear to what extent PhA varies between athletes of different sports and with different types of training (25).

PHASE ANGLE IN HEALTH AND CLINICAL PRACTICE

BIA-derived PhA provides a convenient and non-invasive technique for assessing mortality (31), biomarkers (45, 97, 102), disease severity (10, 33, 53, 75), overall health status (60), quality of life (10, 34, 70), and malnutrition (34, 40, 47, 52, 74, 84) in several clinical populations. PhA is dependent upon body cell mass, and cell membrane integrity, which partially explains the prognostic characteristics of PhA (78), as poor membrane integrity is likely to result in poor cellular function. Within cancer patients and survivors, a PhA cutoff value of 5.6° has been established as a marker of health status and functional capacity (35, 57). PhA is also used as an important prognostic factor of survival in cancer patients (5, 31), as a significant relationship exists between low PhA values and overall survival in individuals with advanced cancer (83). Furthermore, tumor volumes are negatively associated with PhA in patients with non-small cell lung cancer (17).

Also, the cancer diagnosis, resultant treatment, and affected area may be related to PhA. For example, using linear regression, incline bench press 1-repetition maximum explained 28% of the variance in PhA in breast cancer patients (102). Adding lower body muscular endurance and cardiorespiratory fitness in the multiple regression model explained just 4% more of the variance in PhA (R^2 = 0.32) (102). Altogether, this suggests that pectoralis muscular strength was a critical factor in determining PhA which makes sense because the pectoralis region would be the most affected by chemoradiation and surgery, and could explain its influence in predicting PhA.

The utilization of PhA also provides a convenient and non-invasive approach to evaluating and monitoring the overall nutritional status and changes in water compartments of cancer survivors (34, 65), since low PhA values are associated with malnutrition (83). Furthermore, a different study showed that the extracellular-to-total body water ratio as measured with BIA was the best predictor of survival in cancer patients with sarcopenia (32). The authors showed that an extracellular-to-total body water ratio ≥ 0.395 combined with a high neutrophil-lymphocyte ratio had a 3.84-fold risk of mortality compared to patients with low extracellular-to-total body water and neutrophil-lymphocyte ratios (32).

PhA also provides a simple, valid, useful, non-invasive tool for the assessment of nutritional status and malnutrition in people living with HIV (80), patients with anorexia nervosa (57), Crohn's disease (82), hemodialysis patients (47), youth (8), and individuals with cardiovascular disease (41). In psoriatic patients, low PhA is associated with clinical severity, metabolic syndrome, and quality of life (10). PhA has also been shown to be an independent prognostic indicator for cirrhosis and serves as a severity indicator for liver diseases (81). Relative to bone health, a lower PhA is associated with a greater probability of osteoporosis (108). In individuals with type II diabetes mellitus, PhA is used to assess an individual's ability to control fasting blood glucose (20) and is indicative of catabolism (26). The presence of sarcopenia is more likely in subjects with lower PhA values (24), and PhA is a marker of cachexia in patients hospitalized with cardiovascular disease (41). Individuals with cardiovascular disease have lower PhA values than controls (14), and lower PhA values are associated with a higher incidence of cardiovascular disease (53). This relationship is associated with intravascular congestion and plasma volume status (97).

Furthermore, given the underpinnings of PhA and its relation to neuromotor function, as it relates to its dielectric, permittivity, and electric conductivity characteristics, it makes sense that PhA may be highly applicable for measuring function in patients with neuromotor deficits. Notably, PhA was reported to be 2.4 degrees lower in patients with spinal cord injury compared to healthy subjects (4.7° vs. 7.1°), with both healthy and spinal cord-injured male subjects having higher PhA compared to the respective female group (2). Whether a PhA continuum exists that can rate the severity of spinal cord injury remains to be seen. It would be interesting to know if patients with multiple sclerosis (i.e., impaired neural conductivity) have reduced PhA and if it can be related to disease progression.

PhA can be useful in the early identification of risk in patients hospitalized with COVID-19 (3) and can predict hospital stay length (87). In hemodialysis patients, higher PhA values were associated with higher hemoglobin concentrations (a beneficial characteristic as it relates to all-cause mortality in this population) and albumin (47), and lower PhA values were associated with a greater risk of protein-energy wasting and frailty (93). Given the relationships between

PhA and health in a wide range of disease states, there is an obvious need to further understand how PhA can be improved with exercise.

THE UTILIZATION OF PHASE ANGLE IN SPORTS AND RELATIONSHIPS WITH FITNESS AND PERFORMANCE

The assessment and continuous monitoring of body composition is essential in sports due to its relevance to athletes' overall health and performance capacity (70). BIA presents itself as a robust methodology to quantitatively estimate body composition, as BIA is used to measure body fat percentage, fat-free mass, total body water, intracellular water, extracellular water, extracellular to intracellular water ratio, body cell mass, and PhA. Given the speed, safety, and non-invasive nature of BIA, it is an ideal method for monitoring and detecting injuries (18, 67, 68), tracking longitudinal changes in body composition during a season (105) or between seasons (79), and assessing neuromuscular status (11, 12), the efficacy of training interventions (58), and hydration status (18).

PhA is associated with physical activity (69), cardiorespiratory endurance (48, 49, 59, 100), running performance (33), muscular strength (29, 39, 59, 61–63), power (29, 39, 71), sprint performance (63), agility (66), dynamic balance (66), and anaerobic capacity (30,63), but not flexibility (107). Individuals with larger PhA values display superior muscular strength of the upper limbs (30), while low PhA values predict low levels of muscular strength (75). Furthermore, athletes with higher PhA values perform better in anaerobic activities such as sprinting speed, and repeated sprint ability (63), the Wingate test (30), and the vertical jump (76).

Interestingly, changes in PhA are strongly related to changes in vertical jump performance (13), suggesting that PhA may also be used as a tool for evaluating changes in performance-related parameters. The significant and positive association between PhA and running performance also highlights the potential of PhA in monitoring improvements in cardiorespiratory endurance (33). Future research should explore if the associations between PhA and fitness-related performance reflect the adaptations of regular training, and whether changes in the PhA are suitable for monitoring or predicting performance improvements. More specifically, research is needed to determine if improvements in PhA occur with resistance training, anaerobic training, or cardiorespiratory endurance training and if PhA is related to performance. Furthermore, since fluid shifts occur with posture changes, diet, and exercise, research is needed to examine the accuracy of PhA in predicting day-to-day fluctuations in performance markers such as maximal voluntary contractions and other markers of athletic performance.

EFFECTS OF EXERCISE PROGRAMS ON PHASE ANGLE

Exercise induces acute and chronic molecular, cellular, and tissue adaptations which tend to be associated with improved health. Generally, following basic principles of nutrition and physical activity should increase PhA (43), as PhA is significantly higher in active individuals when compared to controls (69). PhA has been shown to be improved after resistance training and concurrent training in young adults, older adults, obese women, and cancer patients (15, 38, 58, 94, 99, 103), whereas yoga did not affect the PhA of cancer patients (27).

A systematic review and meta-analysis in older adults suggest that resistance training that lasts ≥ 8 weeks increases PhA ~0.52 degrees, with a relative increase in Xc and decrease in R, whereas inactivity induced opposing effects (15). Resistance training frequency is an important variable for consideration in exercise-based interventions, as better adaptations in PhA have been found in obese women performing resistance training 3 times per week compared to 1 time per week (110). Resistance training intensity and volume are also likely to influence changes in PhA, as six to ten exercises with twelve repetitions per resisted exercise are recommended to improve PhA (59). Likewise, another study showed that hypertrophy-type resistance training increased PhA in young adult men and women (89).

Furthermore, a comparison of the effect of a constant workload versus ascending pyramidal load resistance training on PhA suggests that both exercise prescription methods promoted similar improvements in PhA (90). However, both the constant load and ascending pyramidal load used an 8–12 repetition maximum (90). Thus, future research should compare the effects of different resistance training intensities amongst the repetition continuum (muscular strength, muscular hypertrophy, and endurance) on PhA (96). It remains unclear if the improved PhA observed from concurrent training programs is a result of resistance training endurance training, or a combination of both. An exploratory study suggests that 6 weeks of resistance training but not endurance or inclined sprint interval running improves PhA in healthy men, and the improvements in PhA were highly related to Xc but not R (103). Interestingly, steady-state endurance training at 85% of critical speed resulted in a 3% decrease in PhA (103). Further exploration of this finding could provide key insights into the effects of exercise-based interventions on PhA, which holds immense implications in both sports and clinical settings. Therefore, future research is required to understand what type of exercise training has the biggest capacity to improve PhA, and if endurance-based training decreases PhA. To our knowledge, no study has explored the effects of maximum velocity sprint interval training, plyometric training, or speed agility and quickness training on PhA. Lastly, the longitudinal effects of different muscular contraction types during resistance training (eccentric, concentric, and isometric) on PhA are yet to be explored. Wide-scale longitudinal studies are needed to determine the optimal training stimulus for improving PhA, and which raw BIA variables have the greatest influence on PhA.

MAJOR TAKEAWAYS AND PRACTICAL APPLICATIONS

PhA is an easily measured variable that relates to cellular function, neural conductivity, and cellular membrane integrity. PhA is likely related to both aerobic and anaerobic adaptations to exercise stimuli, as caveolae may support mitochondrial function, improve action potential propagation, and improve body composition. Empirical evidence suggests that PhA is likely more related to muscular strength when compared to other measures of fitness, suggesting that neuromuscular conductivity, dynamic resting membrane potential, and resistance to cellular breaches from eccentric contractions may be at the forefront of cellular membrane health. Nevertheless, low PhA is associated with diseased states, and exercise may be effective in improving PhA, where higher PhA is a marker of improved health. Still, additional research is needed to understand what type of exercise training would optimize improvements in PhA.

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