Biological/Genetic Regulation of Physical Activity Level: Consensus from GenBioPAC

J. TIMOTHY LIGHTFOOT[1,2], ECO J. C. DE GEUS[2,3], FRANK W. BOOTH[2,4], MOLLY S. BRAY[2,5], MARCEL DEN HOED[2,6], JAAKKO KAPRIO[2,7], SCOTT A. KELLY[2,8], DANIEL POMP[2,9], MICHAEL C. SAUL[2,10], MARTINE A. THOMIS[2,11], THEODORE GARLAND JR[2,12], and CLAUDE BOUCHARD[2,13]

[1]Department of Health and Kinesiology, Texas A&M University, College Station, TX; [2]The Genetic and Biological Determinants of Physical Activity Consortium (GenBioPAC); [3]Department of Biological Psychology, VU University Amsterdam, Amsterdam, THE NETHERLANDS; [4]Departments of Nutrition and Exercise Physiology and Biomedical Sciences, University of Missouri, Columbia, MO; [5]Department of Nutritional Sciences, University of Texas at Austin, Austin, TX; [6]Department of Immunology, Genetics and Pathology, and Science for Life Laboratory, Uppsala University, Uppsala, SWEDEN; [7]Department of Public Health and Institute for Molecular Medicine FIMM, University of Helsinki, Helsinki, FINLAND; [8]Department of Zoology, Ohio Wesleyan University, Delaware, OH; [9]Department of Genetics, University of North Carolina, Chapel Hill, NC; [10]Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana–Champaign, Urbana, IL; [11]Department of Movement Sciences, Faculty of Kinesiology and Rehabilitation Sciences, Katholieke Universiteit Leuven, Leuven, BELGIUM; [12]Department of Evolution, Ecology, and Organismal Biology, University of California, Riverside, CA; and [13]Human Genomics Laboratory, Pennington Biomedical Research Center, Baton Rouge, LA

ABSTRACT

LIGHTFOOT, J. T., E. J. C. DE GEUS, F. W. BOOTH, M. S. BRAY, M. DEN HOED, J. KAPRIO, S. A. KELLY, D. POMP, M. C. SAUL, M. A. THOMIS, T. GARLAND JR, and C. BOUCHARD. Biological/Genetic Regulation of Physical Activity Level: Consensus from GenBioPAC. *Med. Sci. Sports Exerc.*, Vol. 50, No. 4, pp. 863–873, 2018. **Purpose**: Physical activity unquestionably maintains and improves health; however, physical activity levels globally are low and not rising despite all the resources devoted to this goal. Attention in both the research literature and the public policy domain has focused on social–behavioral factors; however, a growing body of literature suggests that biological determinants play a significant role in regulating physical activity levels. For instance, physical activity level, measured in various manners, has a genetic component in both humans and nonhuman animal models. This consensus article, developed as a result of an American College of Sports Medicine–sponsored round table, provides a brief review of the theoretical concepts and existing literature that supports a significant role of genetic and other biological factors in the regulation of physical activity. **Conclusions**: Future research on physical activity regulation should incorporate genetics and other biological determinants of physical activity instead of a sole reliance on social and other environmental determinants. **Key Words:** ANIMAL, BIOLOGY, GENETICS, GENOMICS, HUMAN, PHYSICAL ACTIVITY, SPONTANEOUS ACTIVITY, VOLUNTARY PHYSICAL ACTIVITY

Physical activity promotes health and quality of life, and prevents premature death, with supporting literature reviewed in a number of different places (1,2). Conversely, physical *inactivity* is a root cause of several chronic health conditions, is a major risk factor for obesity and diabetes, and has been reported to be the second leading actual cause of death in the United States (3). Physical activity is considered an effective means of maintaining body weight, a necessary part of any effort to increase or decrease an individual's weight in a stable manner (4–6), a significant environmental modifier of weight (7), and an effective treatment option for some aspects of mental health, such as depression (8,9). Despite the strong evidence favoring physical activity as an effective and cost-effective component of both preventive medicine and therapy, general activity levels in the United States are low, with studies using direct activity measurements suggesting that less than 5% of adults older than 20 yr of age engage in at least 30 min of moderate intensity physical activity daily (10). This trend is not limited to the United States but also has been reported as a worldwide health issue, with the World Health Organization naming physical inactivity as the fourth leading risk factor for global mortality (11). Moreover, community-based attempts to promote physical activity have had mixed success (e.g., 12,13).

Beyond the direct health effects and the reduction in quality of life suffered by those who are not active, physical inactivity imposes significant costs on health care systems. Using admittedly conservative estimates, with consideration

Address for correspondence: J. Timothy Lightfoot, Ph.D., Department of Health and Kinesiology, 4243 Texas A&M University, 645 Lamar Street, College Station, TX 77843; E-mail: TLightfoot@tamu.edu.
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of only the effect on the top 5 noncommunicable diseases globally and ignoring mental health, Ding et al. (14) estimated that physical inactivity costs $67.5 billion yearly in health care expenditures and productivity losses. Other estimates have generated an even higher financial burden on the basis of different models. For example, Chenoweth and Leutzinger (15) reported that the estimated nationwide costs of risk factors due to physical inactivity were approximately $507 billion per year in the United States alone. No matter what model is used, the effect of physical inactivity on just health economics is profound. In fact, given the overall economic effect in conjunction with the effect on health, public health authorities worldwide have launched interventions aimed at increasing physical activity during work/school time, during transportation to work and school, and in leisure time (1,11,16,17).

Despite this wide and deep literature showing the health and economic benefits of physical activity, the widely disseminated physical activity guidelines (1), and the large amount of information and programs available to the public, in general, overall activity statistics have not improved significantly over the past 50 yr. As noted earlier, the most recent large-scale accelerometer database available suggests that only a small minority of US citizens meet physical activity guidelines, with less than 5% of adults, less than 8% of adolescents, and less than 58% of children being classified as "active" (10). These national accelerometer–based numbers are markedly lower than more subjective historic data (Fig. 1) of the estimated activity levels from the Behavioral Risk Factor Surveillance System (BRFSS [18]). The volatility of the more subjective estimates is illustrated by the fluctuations in percentage of adults reportedly engaging in activity from the 2000 to the 2001 BRFSS survey, particularly by the striking rise in physical activity engagement that was largely attributable to a change in the survey questions that were asked regarding physical activity. However, regardless of the metric used, be it the objective measures or the more subjective estimates, it is clear that a significant portion of the global population does not accumulate enough physical activity on a weekly basis to avoid elevated risk, let alone confer health benefits (11).

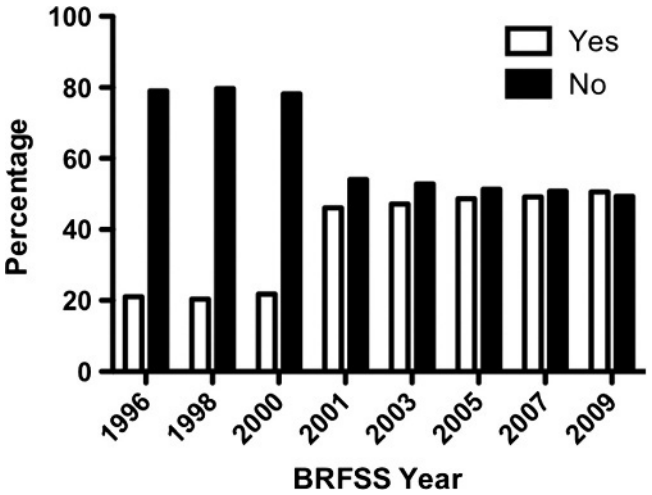

FIGURE 1—Percentage of surveyed BRFSS adults with 30+ min of physical activity 5 or more days a week (1996–2000) or percentage with 30+ min of physical activity or 20+ min of vigorous activity 5 or more days a week.

Why is it that, despite the recognition of the critical role of physical activity in health over the past 50 yr, the number of physically active individuals has not significantly increased? Some have cited technological encroachment or other lifestyle changes as primary factors for the persistently depressed activity levels. The worldwide decrease in the number of occupations requiring physical labor is also part of the explanation (19,20). Furthermore, a large literature indicates potential social and environmental factors that inhibit physical activity level, but this has been—at best—ambiguous and nonconsistent as to which factors are important (19).

Given that all human behavioral traits are usually determined by both environmental/social and biological factors, it is alarming that most of the literature on physical activity (e.g., 19,21) has excluded biological factors as potential determinants of physical activity levels in humans. However, even a brief and targeted literature review as included in this article shows conclusively that physical activity level is strongly influenced by biological mechanisms. The hypothesis that biological mechanisms regulated physical activity level was supported by an early review in this journal (22), and with the advances in genomics and genetics since that time, the foundational science supporting the contention that biological determinants regulate physical activity level has only grown stronger. Thus, the purpose of this consensus article is to provide a brief review of the literature that supports the concept that biological, including genetic and genomic, factors are important determinants and regulators of physical activity level. This brief review is offered to motivate further research aimed at understanding rates of physical activity participation by incorporating biology and genetics in research paradigms.

EVIDENCE OF BIOLOGICAL REGULATION OF PHYSICAL ACTIVITY

In this review, we take the broadest view of "physical activity"—namely, we define physical activity as any locomotion or movement that is the result of skeletal muscle contraction (23). A broad definition of physical activity is important in the present context because it needs to be applicable to both human and animal models, and should allow for the incorporation of spontaneous physical activity (e.g., "fidgeting"), nonexercise activity thermogenesis, and both leisure-time recreational activity and occupational activity. Furthermore, and probably most importantly, we treat physical activity as the *dependent variable*, where the measured amount of physical activity or the energy expenditure caused by physical activity is being investigated, as opposed to the common consideration of physical activity as an *independent*

variable or mediator of change, where activity is manipulated to determine its effect on health or other traits. This implies that the focus is on genes, pathways, systems, tissues, organs, and organ systems influencing physical activity levels.

Some of the earliest suggestions that physical activity levels could be influenced by biological factors were in multiple studies in the 1920s and early 1930s, primarily from Richter and his colleagues (e.g., 24,25), which showed that an unknown internal biological substance associated with reproduction altered running-wheel activity of rats. The "substance" suggested was later identified as the sex hormones, testosterone, and estrogen, and a rich body of work shows clearly that sex hormones can influence activity (e.g., 26). Furthermore, even before DNA was identified, Rundquist (27) in 1933 made the earliest suggestion that heritability influenced physical activity level. Rundquist (27), after selectively breeding rats for 12 generations on the basis of daily activity in rotating-drum cages, noted "It is, then, quite safe to ascribe the major role in the production of the individual differences in this activity to inheritance." Confirmatory data for this conclusion have become overwhelming in the past 80 yr, with at least 45 studies in adult human and mature rodent models showing that individual variation in physical activity is, to an important extent, influenced by genetic variation (28–72).

The relative contribution of the genetic variance to the total variance for a trait in a given population at a certain time is called the "heritability" of the trait and is typically expressed as a percentage. In all models considered, the estimated heritability of physical activity in adults ranges from approximately 20% (67) to 90% (60). These estimates vary on the basis of the activity criterion used, the study design and type of heritability statistics used, the species studied, the gene pool of the study population, age and sex of the organism, and the environmental conditions. In addition, in the human studies that have been able to parse out the differing sources of variability (e.g., 58,60–62,67–69), the role of environmental influences that are experienced similarly by family members (collectively known as "common" environmental factors) has generally been zero, with only one study (67) indicating a small common environmental influence on activity level (≈12%). Thus, the available literature clearly shows that the primary determinants of physical activity are genetic factors and environmental factors that are unique to an individual (i.e., independent of other family members' characteristics), which can consist of the individual's sociodemographic characteristics, personal life history, and social settings, but could also subsume the effects of chance, normal day-to-day variability, and measurement error, depending on the study. For the interested reader, a thorough discussion of

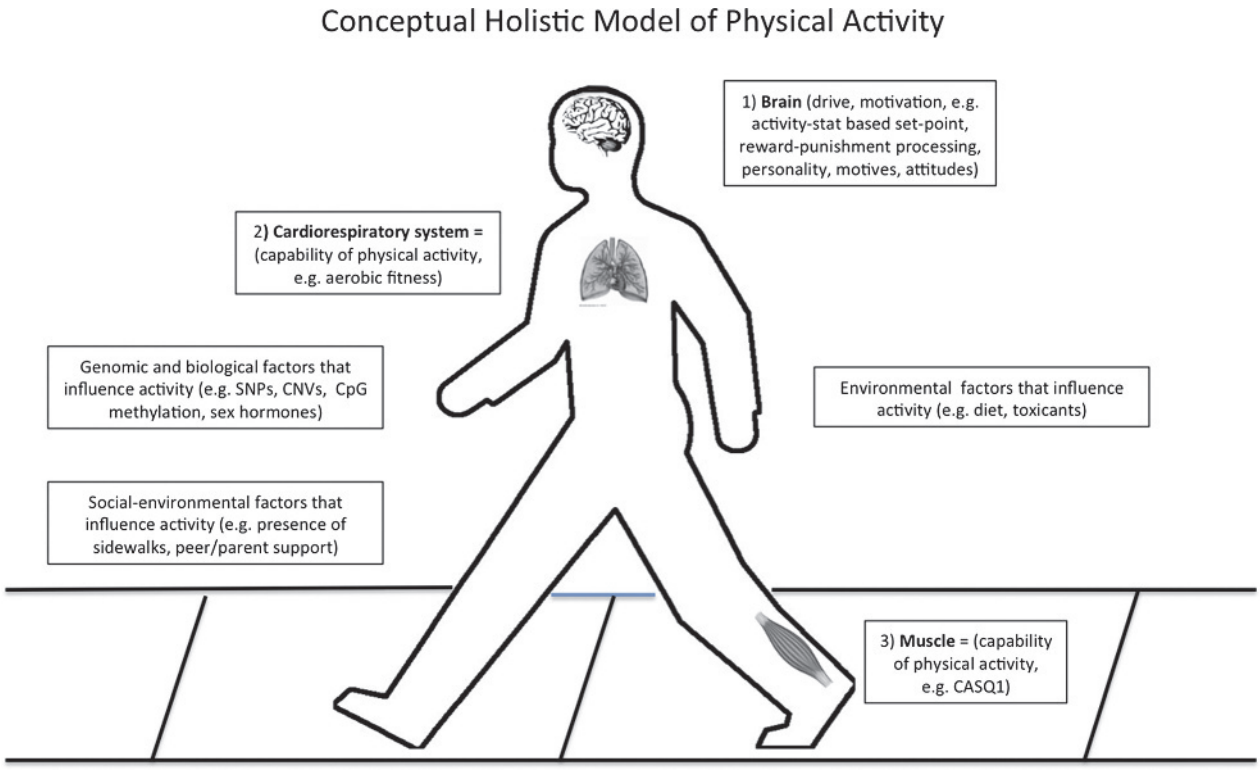

FIGURE 2—Conceptual model for the main physiological systems involved in physical activity and its regulation. 1) The brain is the behavioral control center integrating preset information from the activity-stat (see text) with ongoing motivational state. 2) Duration and intensity of physical activity will depend on cardiorespiratory fitness, partly by viscerosomatic signals (e.g., becoming out of breath) that affect motivational state. 3) Muscle is the mechanism of action (effector) and performance capability of this unit, as well as the cardiorespiratory system, is necessary but not sufficient for physical activity. Effects of biological, including genetic/genomic and environmental factors, with many interactive effects, will determine individual differences in the functioning of these physiological systems and hence the level of physical activity.

the phenotypic variance and its genetic and environmental components and subcomponents can be found in standard genetics textbooks.

Figure 2 provides a conceptual model of the biological determinants of physical activity, divided into three main components (brain, cardiorespiratory system, muscle), all of which can interact. All three components can have a substantial genetic basis but are also influenced by various factors in the external environment. Importantly, this model of multifaceted regulation includes both central (brain) and peripheral (cardiorespiratory, muscle) control components. A preset, brain-located "activity-stat" was earlier hypothesized (22), and it was proposed that it would not only serve as a preprogrammed activity-level controller but also receive signals from various other factors that may themselves be partly genetically regulated, such as sex hormone levels, dietary habits, and exposure to toxicants. The activity-stat was seen as part of a much larger motivational regulatory system that integrates reward and punishment cues related to ongoing or recently completed physical activity, arising from afferent somatovisceral feedback in cardiorespiratory and muscle (fatigue) sources. In humans, motivational states are further modulated by trait-dependent individual differences in the drive to be active related to personality, social support, or the many social–environmental opposing or enabling factors for physical activity. The science has evolved since an activity-stat was part of the discussion on the regulation of physical activity level, and the concept is hard to justify today (e.g., 73). It is now better appreciated that the regulation of behavioral traits is influenced by complex multifactorial and redundant genetic, epigenetic, and other biological systems, with each component characterized by small effect sizes.

This conceptual holistic model of the control of physical activity in which genetic and other biological factors play a key role is supported by a variety of literature. The use of the conceptual model in Figure 2 is critical in further studying, understanding, and altering physical activity, as well as driving future research directions (Fig. 3). The existing literature, while having several gaps, is robust enough to conclude that investigators studying physical activity—as well as policy makers pondering relevant policies—must consider all factors in their deliberations and not just focus on social–environmental aspects.

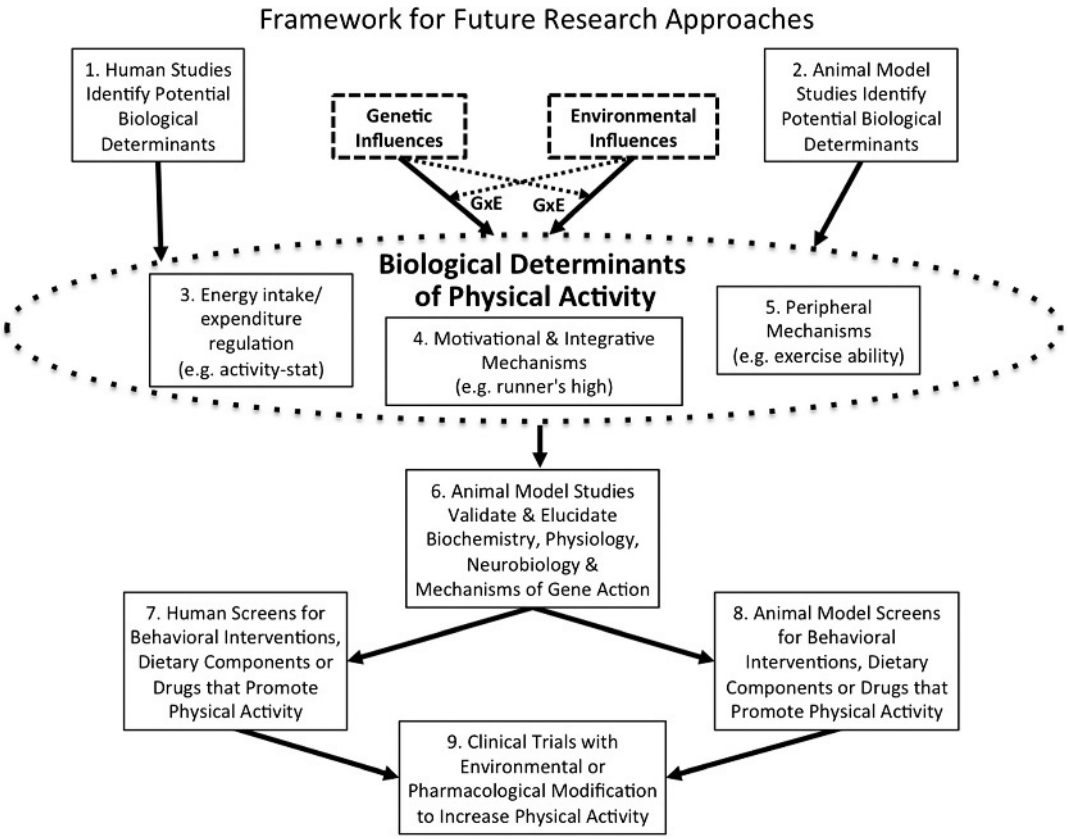

FIGURE 3—Research directions to further unravel the biological regulation of physical activity level. The three major sources of individual differences in physical activity level are genetic variants, environmental influences, and their interplay. Strategies to understand the biology of physical activity regulation and the contribution of genetic and environmental factors are numbered 1 to 9. Studies of humans and of animal models play complementary roles. The ultimate goal is to identify safe and effective environmental and/or pharmacological interventions that can increase the level of physical activity.

BIOLOGY OF REGULATION OF PHYSICAL ACTIVITY LEVEL AND FUTURE RESEARCH DIRECTIONS

Although a significant amount of evidence in both humans and rodents shows that daily physical activity level is genetically controlled to a significant extent, the specific mechanisms involved are still incompletely delineated. Efforts to identify from where in the genome this regulation arises have used genome-wide association studies, positional cloning approaches, and other -omics technologies in both humans and rodents. These efforts, including the use of large-scale twin studies (68,69,74) and both inbred (e.g., 64,66) and selectively bred animal models (e.g., 23,70,75–77), have been fruitful in identifying promising quantitative trait loci (QTL; i.e., chromosomal locations) associated with physical activity level. Furthermore, it has been suggested using cross-sectional designs in humans (e.g., 69) and longitudinal designs in rodents (71) that the genetic influence on activity level varies by age, increasing toward the end of puberty and waning as the individual reaches later ages. In addition, a few rodent studies have documented genetic dominance (e.g., 78) and epistasis (79,80), as well as pleiotropic interactions (81) in regard to physical activity level. There have been successes in determining the genetic underpinnings of some muscle traits in mice selectively bred for high activity (e.g., the mini-muscle phenotype [82,83]) as well as providing expression QTL results from these mice (76,84). These studies have resulted in initial summary genomic maps of QTL associated with activity, as well as suggested candidate genes involved in regulating physical activity (85), with limited data from congenic animals supporting some of these genetic associations (e.g., 86,87). However, as noted (85), most potential candidate genes still lack rigorous validation, which is a widespread issue when working to move candidate genes from the "associative" to "causative" category in regard to any phenotype (88). Furthermore, although some authors have discussed translation of rodent results into humans (85), the only study that has attempted to translate between mouse and human data in the same study (89) suffered from critical design issues (e.g., incorrect translation of low-active mouse QTL onto high-active humans, rejecting objective measures of human activity in favor of subjective measures) that limited interpretation of the results. Given the amount of both human and rodent data available, more translational efforts need to be conducted.

Besides using traditional genetic approaches to illuminate the genetic component of activity level, some investigators have taken a hypothesis-driven approach targeting specific factors that may influence daily activity in one or more of the areas shown in Figures 2 and 3. Given the ability to interrogate a wide variety of tissues, most of this work has been in animal models, the human translatability of which has been discussed in several venues (e.g., 23,90). For example, research in the biological regulation of physical activity level has focused on several specific areas depicted in the conceptual model as defined in Figure 2:

- the central reward center of the brain (primarily structures in the striatum) as a major site of physical activity regulation;
- the peripheral cardiovascular and musculoskeletal capabilities associated with high- and low-activity profiles in animal models;
- genomic and other biological factors, such as sex and other hormones, and illness and disease, which may cause changes in inflammatory signals and metabolite levels that participate in the regulation of daily physical activity level;
- environmental factors such as diet and the presence of environmental toxicants that may augment/inhibit physical activity level regulatory mechanisms; and
- social–environmental factors that may influence activity.

Research focused on central mechanisms regulating physical activity level has provided evidence of altered dopaminergic (91,92) and differential endocannabinoid activity (93–95) in the brains of highly active animals. Garland's group (e.g., 23,76,84,92) in particular has worked to elucidate the neural control of high levels of voluntary exercise in selectively bred lines of mice. More recently, Roberts et al. (e.g., 96) have used a selectively bred rat model to investigate the neural control of low versus high voluntary exercise on wheels. In addition, early efforts have been presented at describing the central transcriptomic (97,98) and proteomic signatures of high- and/or low-active animals (99), along with efforts to produce transient gene silencing to investigate neural candidate genes in whole animals (100).

Common sense and various lines of research indicate that even if an animal has a high neural drive to be physically active (e.g., arising from the nucleus accumbens), without the physiological capability for extended activity, it will not be able to be highly active (e.g., 23,84). As such, a variety of studies have suggested the importance of heritable peripheral components—primarily in the skeletal muscle—in the determination of activity level. Tsao and coworkers' (101) intriguing data showed that mice with overexpressed glucose transporter 4 (Glut4/*Slc2a4*) also exhibited a fourfold increase in voluntary wheel running. The authors suggested that augmented substrate availability caused this increase in activity, implying that daily activity could be regulated by substrate-delivery mechanisms in the muscle. Presuming the genetic manipulation primarily affected ability for endurance exercise, this finding implies that the wild-type mice had an excess central "drive" to be physically active, or that this drive was increased by the genetic manipulation. In addition, Meek et al. (102) showed that mice bred for high voluntary exercise on wheels and that had reached a plateau in their breeding-induced activity levels increased wheel-running activity when fed a high-fat, high-sucrose diet. Again, however, it is possible that this diet affected motivation for, or reward received from, wheel running, rather than just exercise ability (102).

Furthermore, Pistilli et al. (103) showed that knocking out IL-15Rα, which influences substrate usage particularly in fast-twitch fibers, increased daily wheel running, whereas O'Neill et al. (104) noted that knocking out AMPK ß1ß2 decreased wheel running. As noted earlier, work from Garland's group (78,82,83) with the mini-muscle phenotype in their selectively bred high active animals has revealed a recessive allele that results in a 50% reduction in the mass of the triceps surae muscle complex and of total hindlimb muscle mass with a doubling of the mass-specific aerobic capacity and an altered fiber-type composition and contractile performance, along with an increase in size of the animal's heart ventricles, liver, and spleen. As with central mechanisms, initial work has been published regarding differing skeletal muscle proteomes of high- and low-active animals (105), with preliminary work considering the effect of transient gene silencing on some of the proteins overexpressed in highly active animals (100).

The idea that both peripheral and central mechanisms contribute to the regulation of physical activity level (Fig. 2) has been reinforced by literature on the determinants of voluntary exercise behavior in humans (106). Instrumental conditioning—which has been defined as operant conditioning that pairs a response with a reinforcement (107)—plays a key role in many voluntary behaviors, and exercise seems no exception. When people engage in regular exercise activities, they are exposed to a combination of acute (during the exercise bout and shortly after) affective effects, which are in part experienced as pleasant and in part as unpleasant (108). The net balance of these effects determines whether the activity will be experienced as punishing or rewarding, respectively, and this balance will strongly contribute to the adoption and maintenance of regular exercise behavior, or the failure to do so. Previous studies showed a robust association between a more favorable affective response (i.e., relating to moods, feelings, and attitudes) during exercise and the intention to engage in voluntary exercise (109,110) as well as greater actual participation in (voluntary) moderate to vigorous exercise (111–115).

Various potential modulators of the affective response have been shown to influence regular exercise behavior in humans, including personality and self-regulation. Regular exercisers score lower on neuroticism and higher on extraversion, conscientiousness, and sensation seeking (116–119), "brain" traits known to be under substantial genetic control (120). Neuroticism may increase the fear of embarrassment or injury, which are often cited as perceived barriers to exercise. Introverts, with a high intrinsic arousal level, might be easily overstimulated and less attracted to exercise activities, particularly in socially rich contexts. Self-regulation or the related concepts of self-motivation and conscientiousness are well-known correlates of regular exercise behavior program (121–123). This is not surprising, because the ability to endure the temporary discomforts of exercise in view of a future reward (e.g., physical fitness, losing weight, winning the game) or a long-term goal (health, ability to attract romantic partners) is a core characteristic of self-regulation. Perhaps less well known is that self-regulation is itself a heritable trait (124) as are motives for activity (125). Self-regulation should therefore be considered as part of the biological network that regulates the level of physical activity.

Exercise ability can also modulate the affective response to exercise in humans. Being good at exercise and performing better than others will lead to feelings of competence, whereas lower levels of performance might lead to disappointment or shame. Perceptions of differences in exercise ability may strongly contribute to the affective response to exercise. These perceptions will largely but not perfectly reflect actual exercise ability. The latter may be influenced by skills specific to a sport, but a number of general fitness characteristics, including strength and endurance, are strong predictors of performance across a variety of sports and exercise activities (126). These general fitness characteristics are known to be highly heritable, and this applies to individual differences encountered in cross-sectional samples (127,128) as well as in the response to a fixed training regime (129). In the latter case, being a good responder to regular exercise for a relevant biological trait (e.g., exercise capacity) is likely to augment rather than diminish the interest in remaining physically active. One could hypothesize that the opposite would be true for a poor responder to the same exercise regimen.

The heritable influence on exercise ability might be especially relevant for self-chosen levels of exercise behavior during late adolescence, when the influence of role models in health behaviors is large (130). Likewise, the association of extraversion and sensation seeking with exercise behavior might be particularly prominent in adolescence, when many exercise activities are performed in teams with friends and peers. This may explain the relatively high levels of heritability that are noted for exercise behavior in mid and late adolescence (131).

In addition to work on both central and peripheral genetically influenced physical activity regulatory mechanisms, a large and deep, though somewhat dated, pool of literature addresses the effects of sex hormones on physical activity. This body of literature, as noted earlier, reaches back to the mid-1920s, but showed resurgence in the early 2000s. Seminal work by Roy and Wade (132) suggested that estrogen was the primary driver of physical activity, primarily through aromatase mechanisms. However, more recent direct testing of that hypothesis with both reversible and nonreversible aromatase inhibitors, as well as modern methods of exogenous hormone supplementation, have suggested that testosterone may actually be primary in the sex hormone effects on physical activity (133,134). Although sex hormones have a significant effect on physical activity, it remains an open question whether their regulation of physical activity arises from genetic mechanisms (e.g., some variation in the androgen receptor gene) or whether the sex hormone effect is a modifier of other, more basic genetically controlled regulatory pathways (e.g., effect on dopaminergic signaling pathways). Also unclear is the extent to which sex

differences in physical activity in rodents and humans are caused by physiological differences invoked by differences in hormone production (e.g., more testosterone, more muscle mass, different activity choice) or by direct regulation of activity due to the differences in their hormonal milieu (e.g., 134).

Lastly, modification of genetic regulation of activity by unique-to-the-individual environmental factors—either through epigenetic mechanisms or through direct inhibition/augmentation of the genetic mechanisms of control—is still a relatively unexplored area. Results from the late 1800s suggested that diet could affect physical activity level (135), and it is well known and accepted that certain experimental paradigms that moderately reduce caloric intake will reliably increase physical activity in rodents and nonhuman primates (136–138) and probably humans (139,140). Interestingly, altering dietary composition in selectively bred, highly active mice markedly increases activity (102,141), whereas feeding a high-fat, high-sugar diet in inbred mice resulted in large reductions in daily activity in both sexes (142). It is currently unclear if these diet-induced alterations in activity are moderated through hormonal alterations (e.g., ghrelin/leptin or sex hormone changes [143–145]), through a direct effect on central neurotransmitters (e.g., serotonin pathways [146]), or simply due to alterations in substrate availability for activity (102). In addition, early-life exposure to unique environmental toxicants, such as a common plasticizer (benzyl butyl phthalate), may inhibit lifelong activity in offspring through alterations in sex hormone levels or other biological mechanisms when their mothers are exposed to physiologically relevant doses during pregnancy (147). Also, it has been suggested that maternal diet (148) or exercise in and of itself may affect the activity level of the offspring (149,150).

In summary, a large and growing body of literature examines the various areas of potential biological control of physical activity level in both humans and other animals. This literature provides the foundation for the recommended research flow as outlined in Figure 3; this research flow is predicated on the results from previous studies of both human and rodent models, as well as on existing results on the basis of genetic methods and environmental inputs. Current consensus recommends that future research in the biological control of physical activity concentrate on three areas: central neural mechanisms providing the "drive to be active" (motivation), peripheral mechanisms that provide the "capability to be active" (capability), and integrative and mediating biological mechanisms and factors that inhibit or augment the central and peripheral mechanisms (e.g., aspects of endocrine function [151]). This level of research will provide a further foundation for future basic investigations that can be translated into both human and animal studies, with the ultimate goal of developing physical activity–based trials aimed at investigating specific activity regulators.

In conclusion, it is well established that physical activity is healthy behavior, but worldwide levels of physical activity remain low despite the increased emphasis and knowledge available to the general population. The preponderance of literature in sports medicine and exercise science has treated physical activity regulation as a largely nonbiological construct, and this perspective is reflected in the main intervention approaches to increase daily physical activity. Such interventions focus on goal setting, social support, and behavioral reinforcement through self-reward, structured problem solving, and relapse prevention. Although these social–behavioral approaches make good sense, an undisputed body of empirical data also reveals that biological determinants play an important role in the regulation of daily physical activity in both humans and other animals. They do so by influencing brain circuitry related to some of the core elements in the social–behavioral models, including personality, affect regulation, and reward processing, or by influencing cardiorespiratory and muscle capacity to regularly engage in physical activity, which we expect to be closely tied to physical self-efficacy, another core element in social–behavioral models of physical activity. The existence of individual differences in physical activity behavior is undeniable, as is the fact that biological/genetic mechanisms are largely responsible for those differences. Choosing not to investigate these mechanisms would be irresponsible and would hinder the science or understanding the causes of this critical health issue. Thus, future research needs to focus on investigating and identifying these biological pathways participating in the regulation of physical activity level; how they are affected by genetic variants; early-life experiences; epigenetic events; biological intermediates and environmental factors, such as diet and toxicant exposures; and how they affect our attempts to intervene on physical activity level. In keeping with the acknowledged importance of the interplay of nature and nurture in many other behavioral traits, it is the consensus of this authorship group that future research on physical activity regulation should prominently include the identification of the biological determinants of physical activity instead of a sole reliance on the social/environmental determinants.

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