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Paternal Diet, Physical Activity, and Lifestyle as Determinants of Placental Development and Offspring Health: A literature review

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Abstract

For decades, paternal health was considered largely irrelevant to pregnancy outcomes, with scientific and clinical attention focused almost exclusively on maternal physiology. This perspective has shifted markedly over the past fifteen years. A growing body of evidence now indicates that paternal diet, physical activity, metabolic status, and broader lifestyle factors exert measurable influences on embryonic development, placental function, and long-term offspring health. These effects are mediated through multiple biological pathways, including sperm DNA methylation, histone retention, small non-coding RNAs, seminal plasma signaling, and immune–metabolic interactions at the time of implantation.

Human studies demonstrate that paternal obesity and poor metabolic health are associated with altered sperm epigenetic profiles, dysregulation of imprinted genes such as *IGF2*, and increased risks of adverse pregnancy outcomes. Experimental models further reveal that paternal dietary imbalance—both undernutrition and overnutrition—can impair placental vascularization, induce hypoxia, and program sex-specific metabolic phenotypes in offspring. Conversely, paternal physical activity appears capable of partially counteracting diet-induced epigenetic disruptions, improving offspring metabolic health via modifications of the sperm RNA payload.

This narrative review synthesizes evidence from human observational studies, controlled animal experiments, and mechanistic epigenetic research to examine how paternal diet, exercise, and lifestyle shape placental development and offspring health. Particular attention is given to the relevance of these findings for sport science and public health, highlighting paternal preconception health as a modifiable determinant of developmental outcomes.

Keywords

Placental development, Developmental origins of health and disease (DOHaD), Preconception lifestyle, Offspring metabolic health, Intergenerational health

Introduction

The biological role of the father in reproduction has long been framed in minimalist terms. Within classical obstetrics and developmental biology, paternal contribution effectively ended at fertilization, while maternal physiology was assumed to govern all subsequent developmental processes. This conceptual asymmetry was partly pragmatic—pregnancy unfolds within the maternal body—but it also reflected an incomplete understanding of how environmental information can be transmitted through the male germline.

Over the past two decades, this view has been increasingly challenged. Evidence from the field of Developmental Origins of Health and Disease (DOHaD) has expanded the temporal window of developmental sensitivity to include the periconceptional period, during which parental health and environmental exposures exert disproportionate influence on long-term outcomes [6]. Within this framework, paternal factors have emerged not as peripheral modifiers but as biologically active determinants.

Early human evidence came from studies of paternal obesity. Donkin et al. (2016) demonstrated that obese men exhibit widespread alterations in sperm DNA methylation, affecting genes involved in development, metabolism, and neurogenesis [1]. Importantly, these epigenetic signatures were shown to be partially reversible following bariatric surgery, suggesting that paternal germ cells retain a form of environmental memory that is responsive—but not infinitely plastic.

Parallel epidemiological studies have reinforced the clinical relevance of these findings. Increased paternal body mass index (BMI) has been associated with impaired gamete quality, altered embryonic development, pregnancy complications, and elevated risks of pregnancy loss, even after controlling for maternal factors [7,8]. Such observations undermine the notion that paternal health is biologically inconsequential once fertilization has occurred.

For much of modern reproductive science, the biological role of the father has been implicitly minimized. Paternal contribution was traditionally framed as limited to the delivery of genetic material, while maternal physiology was assumed to govern implantation, placental development, and fetal growth. This maternal-centric paradigm shaped not only research priorities but also clinical practice and public health messaging, reinforcing the assumption that paternal health before conception was largely irrelevant.

Over the past two decades, this view has been increasingly challenged by evidence emerging from the Developmental Origins of Health and Disease (DOHaD) framework. Fleming et al. (2018) demonstrated that the periconceptional period represents a critical window of developmental sensitivity, during which parental environmental exposures can exert long-lasting effects on offspring health. Importantly, this concept extends beyond maternal influences and provides a theoretical foundation for examining paternal contributions to early developmental programming.

Within this context, accumulating epidemiological and mechanistic studies have begun to document independent paternal effects. Increased paternal body mass index has been associated with impaired gamete quality, altered embryonic development, and adverse pregnancy

outcomes, even after adjustment for maternal factors [7,8]. Parallel advances in sperm epigenetics have further undermined the notion of paternal biological passivity, demonstrating that spermatozoa carry environmentally responsive epigenetic information capable of influencing early embryogenesis [1,9].

Giannubilo (2024) has explicitly framed this historical neglect of paternal biology as the "bad father" phenomenon, arguing that the marginalization of paternal influences reflects outdated conceptual assumptions rather than biological reality[10]. By emphasizing that fathers contribute not only genetic material but also epigenetic, metabolic, and environmental signals, this critique provides an important conceptual lens through which recent findings can be interpreted. Rather than assigning blame, the "bad father" concept highlights a systemic gap in reproductive research and care.

Taken together, these perspectives support a fundamental reframing of paternal involvement in pregnancy biology. Recognizing paternal health as a biologically active and modifiable determinant of placental development and offspring health allows for a more integrative understanding of early developmental processes and sets the conceptual foundation for the present review.

Although the placenta develops within the maternal uterus, it is genetically fetal and thus partially paternal. This simple fact has profound implications. The placenta expresses numerous paternally derived genes that regulate trophoblast proliferation, vascular development, and nutrient transport. As a result, paternal epigenetic disturbances may be disproportionately manifested in placental structure and function.

Experimental studies strongly support this notion. Jazwiec et al. (2022) demonstrated that paternal obesity induces placental hypoxia, impaired vascularization, and sex-specific alterations in placental morphology in mice [3]. Male and female placentae responded differently to paternal metabolic stress, suggesting that paternal signals interact with fetal sex to shape placental adaptation.

Further complexity arises from the role of seminal plasma. Watkins et al. (2018) showed that paternal diet alters the cytokine and signaling profile of seminal plasma, which in turn modulates maternal immune responses during implantation [11]. Even when sperm from healthy males were used, exposure to seminal plasma from metabolically compromised males impaired implantation and early placental gene expression. This finding challenges the sperm-centric view of paternal influence and highlights the importance of paternal–maternal immune communication.

While obesity has received the greatest attention, paternal dietary quality more broadly also plays a critical role. Micronutrient availability, particularly folate, has emerged as a key determinant of sperm epigenetic integrity. Lambrot et al. (2013) showed that paternal folate deficiency in mice alters sperm DNA methylation and increases the risk of congenital abnormalities and placental dysfunction [12] Subsequent systematic reviews have confirmed associations between paternal folate status, sperm quality, and pregnancy outcomes in humans [13].

Importantly, paternal nutritional stress is not limited to excess. Both undernutrition and protein restriction have been shown to impair early embryonic development and placental growth. Morgan et al. (2024) demonstrated that paternal undernutrition alters semen composition and disrupts preimplantation embryo kinetics in mice [4]. These findings complicate simplistic

narratives that focus exclusively on obesity and instead point toward a broader concept of paternal nutritional balance.

From the perspective of sport science, the emerging evidence on paternal health is particularly relevant. Physically active men, including athletes, often experience substantial fluctuations in energy availability, training load, oxidative stress, and hormonal balance. While regular physical activity is generally beneficial, excessive training, inadequate recovery, or poorly matched nutrition may introduce epigenetic stressors during spermatogenesis.

At the same time, exercise appears to be one of the few paternal interventions with consistently positive intergenerational effects. Costa-Júnior et al. (2021) demonstrated that paternal exercise improves offspring metabolic health via epigenetic modulation of the germline [5] These findings suggest that physical activity is not merely a confounder in paternal health studies but a biologically active exposure deserving targeted investigation..

Paternal Diet as a Determinant of Placental Development and Offspring Health

Paternal obesity has traditionally been discussed primarily in relation to impaired semen parameters, including reduced sperm concentration, motility, and increased DNA fragmentation. While these associations are well established, limiting the discussion to semen quality alone risks underestimating the broader biological consequences of paternal adiposity. Increasing evidence suggests that paternal obesity influences pregnancy outcomes and placental development through systemic, metabolic, and epigenetic pathways that extend well beyond fertilization.

Human epidemiological data provide particularly compelling support for this broader perspective. In a prospective cohort study, Lin et al. demonstrated that increased paternal body mass index was independently associated with a higher risk of pregnancy complications and altered fetal growth, even after adjustment for maternal BMI and other confounding factors [14]. This finding is critical, as it supports the existence of a distinct paternal contribution rather than merely shared lifestyle or genetic influences.

At the molecular level, paternal obesity has been consistently linked to alterations in sperm epigenetic profiles. Donkin et al. reported widespread changes in sperm DNA methylation among obese men, affecting genes involved in embryonic development, metabolic regulation, and cellular growth [1]. Such epigenetic disturbances may influence early embryonic gene expression and bias developmental trajectories toward suboptimal placental function.

Experimental evidence further strengthens this interpretation. Jazwiec et al. demonstrated that paternal obesity induces placental hypoxia, impaired vascularization, and dysregulated angiogenic signaling in mice, even in the absence of maternal metabolic pathology [3]. Together, these findings indicate that paternal obesity should be viewed not merely as a fertility-related issue but as a biologically meaningful determinant of placental architecture and function.

Beyond epidemiological associations, paternal obesity has been proposed to exert its effects through epigenetic dysregulation established during spermatogenesis. Houfflyn and Matthys provided one of the earlier integrative syntheses linking male obesity to epigenetic alterations in sperm, emphasizing changes in DNA methylation, histone retention, and chromatin

organization [15]. Importantly, their work highlighted that obesity-related epigenetic disturbances may persist beyond fertilization and influence early embryonic development.

The authors argued that metabolic stress associated with obesity creates an altered epigenetic milieu within the male germline, predisposing offspring to long-term metabolic dysfunction. This conceptual framework anticipated later experimental findings demonstrating placental impairment, altered growth signaling, and increased disease susceptibility in offspring exposed to paternal obesity. By positioning epigenetic inheritance as a central mechanism, Houfflyn et al. provided a critical bridge between clinical observations and molecular evidence.

While maternal overweight has long been recognized as a determinant of adverse pregnancy outcomes, increasing attention has been directed toward the independent contribution of paternal adiposity. Building on earlier conceptual work linking male obesity to epigenetic dysregulation in sperm [15], more recent human evidence indicates that paternal preconception overweight and obesity are associated with impaired gamete quality, altered embryonic development, and increased cardiometabolic risk in offspring, even after adjustment for maternal factors [16].

Importantly, this dual line of evidence suggests that paternal effects operate through both molecular and population-level pathways. Epigenetic alterations described in obese males may provide a mechanistic substrate for the clinical associations observed in human cohorts. At the same time, the persistence of paternal effects after controlling for maternal characteristics underscores that paternal overweight should not be treated merely as a correlated exposure or residual confounder.

Hieronimus and Ensenauer further emphasized the preventive potential of addressing paternal health before conception, arguing that lifestyle modification in both parents represents an underutilized opportunity to reduce intergenerational disease risk [16]. This integrative perspective reinforces the need to conceptualize parental overweight as a shared, yet biologically independent, determinant of developmental programming.

Beyond excess energy intake, specific micronutrient deficiencies have emerged as critical modulators of paternal epigenetic programming. Folate, in particular, plays a central role in one-carbon metabolism and DNA methylation. Lambrot et al. demonstrated that paternal folate deficiency alters sperm DNA methylation patterns and increases the risk of adverse pregnancy outcomes in mice [12].

These findings are supported by human evidence. A systematic review and meta-analysis by Hoek et al. linked paternal folate status to sperm quality, pregnancy outcomes, and epigenetic markers, underscoring the translational relevance of folate-mediated pathways [13]. More recent work suggests that folate deficiency may also increase de novo mutation rates, further compounding developmental risk [17].

The effects of paternal diet are not limited to single micronutrients. Experimental studies indicate that overall dietary composition, particularly protein balance, plays a key role in shaping placental development. Morgan et al. demonstrated that both paternal undernutrition and overnutrition alter semen composition, preimplantation embryo kinetics, and subsequent developmental trajectories [4].

In a related study, paternal low-protein diet was shown to impair fetal growth and placental development, effects that could be partially modified by methyl-donor supplementation [18].

These findings suggest that paternal diet influences placental function through complex interactions between nutrient availability, epigenetic programming, and early embryonic signaling.

Emerging evidence indicates that paternal dietary effects are mediated not only through DNA methylation but also via sperm small RNAs and chromatin remodeling. RNA-mediated inheritance has been demonstrated in the context of diet-induced obesity, with sperm RNA injections sufficient to reproduce metabolic phenotypes in offspring [9,19]

These findings support the concept that paternal diet establishes a multilayered epigenetic signal that influences early embryonic gene regulation. Such mechanisms likely interact with placental development indirectly by shaping early lineage allocation and trophoblast differentiation.

Khoshkerdar et al. (2021) further argued that paternal metabolic health influences maternal physiology during pregnancy, including inflammatory markers and uterine immune responses [20]. Such interactions likely shape placental development long before fetal organs begin to differentiate.

Taken together, current evidence indicates that paternal diet influences placental development and offspring health through a constellation of interconnected mechanisms rather than a single linear pathway. Changes in sperm DNA methylation, altered imprinting of growth-regulating genes, modifications of sperm small RNA profiles, and diet-dependent shifts in seminal plasma composition appear to act in parallel during the periconceptional period.

An important contribution to this integrative view is provided by Pascoal et al., who reviewed mechanistic evidence demonstrating that paternal diet affects spermatogenesis and offspring health primarily through epigenetic pathways [21]. Their work highlights that dietary composition not only disrupts epigenetic programming under adverse conditions but may also represent a potential point of intervention through food-derived bioactive compounds.

From a broader perspective, integrative narrative reviews such as that by Jahan-Mihan et al. emphasize that paternal diet cannot be considered in isolation from body weight and physical activity [22]. Nevertheless, significant limitations remain. Many experimental studies rely on extreme dietary manipulations, while human studies often depend on self-reported intake and lack direct placental endpoints. Despite these constraints, the convergence of evidence supports a central conclusion: paternal diet represents a biologically meaningful and potentially modifiable determinant of placental development.

Paternal Physical Activity, Lifestyle, and Environmental Exposures

While paternal diet has received increasing attention, it represents only one dimension of preconception health. Physical activity, psychosocial stress, sleep patterns, environmental exposures, and substance use all shape the male germline during spermatogenesis. Unlike diet, which often acts through metabolic pathways, these lifestyle factors exert their effects through neuroendocrine regulation, oxidative balance, inflammatory signaling, and epigenetic remodeling. Together, they form a complex network of exposures that influence placental development indirectly but meaningfully.

Physical activity is one of the few paternal exposures consistently associated with beneficial intergenerational outcomes. In contrast to obesity or undernutrition, which introduce metabolic stress, regular moderate exercise appears to promote epigenetic stability in sperm.

Costa-Júnior et al. (2021) demonstrated that paternal exercise in mice improved glucose tolerance, insulin sensitivity, and lipid metabolism in offspring, effects mediated by changes in sperm small RNA profiles [5]. These findings are particularly relevant for sport science, as they suggest that physical activity modifies not only somatic health but also germline signaling.

Mechanistically, exercise reduces systemic inflammation, improves mitochondrial function, and normalizes hormonal rhythms, all of which influence spermatogenesis. Shi and Qi (2023) emphasized that testosterone and cortisol fluctuations during sperm maturation can alter DNA methyltransferase activity and histone modifications [23]. Exercise-induced hormonal balance may therefore stabilize epigenetic programming at critical developmental loci.

However, the relationship is unlikely to be linear. Excessive training loads, inadequate recovery, or chronic energy deficiency—conditions not uncommon in competitive athletes—may introduce oxidative stress and suppress reproductive hormones. While direct evidence linking overtraining to adverse placental outcomes is lacking, the mechanistic plausibility warrants caution.

An emerging theme in the literature is that physical activity may buffer, though not fully reverse, the epigenetic consequences of poor diet. Skerrett-Byrne et al. (2025) showed that paternal exercise partially mitigated the adverse placental and metabolic effects of unhealthy diets, whereas sedentary behavior amplified them [24].

This interaction complicates simplistic public health messages. Exercise alone may not fully compensate for severe metabolic dysfunction, but it appears capable of shifting the developmental trajectory toward resilience. From a preventive perspective, this positions physical activity as a critical component of paternal preconception care.

Psychological stress is increasingly recognized as a biologically relevant paternal exposure. Chronic stress elevates glucocorticoid levels, disrupts testosterone production, and alters epigenetic enzyme activity within the testes.

Akhatova et al. (2025) reviewed extensive evidence showing that stress modifies sperm DNA methylation, histone retention, and microRNA expression[25]. In rodent models, paternal stress has been associated with altered placental weight, dysregulated placental glucocorticoid metabolism, and impaired fetal growth.

Human data remain limited and often rely on self-reported stress measures. Nonetheless, Carter et al. (2023) identified psychological stress as a modifiable paternal risk factor associated with adverse pregnancy outcomes [26]. These findings suggest that paternal mental health may indirectly shape placental development via endocrine and immune pathways.

3.4 Sleep, Circadian Disruption, and Reproductive Signaling

Sleep patterns and circadian alignment are rarely addressed in paternal health research, yet they play central roles in hormonal regulation. Testosterone secretion follows a circadian rhythm, and chronic sleep deprivation is known to suppress reproductive hormones.

Shi and Qi (2023) argued that circadian disruption during spermatogenesis may impair epigenetic maintenance mechanisms, particularly those governing imprinting and chromatin remodeling [23]. Although direct evidence linking paternal sleep to placental outcomes is sparse, the mechanistic foundation suggests this is a significant gap in the literature.

Given the prevalence of shift work and irregular training schedules among athletes, this omission is particularly relevant to sport science.

Beyond lifestyle behaviors, environmental exposures represent an underappreciated dimension of paternal influence. Exposure to endocrine-disrupting chemicals, air pollution, pesticides, heavy metals, and heat stress has been associated with impaired sperm quality and altered epigenetic profiles.

Akhatova et al. (2025) highlighted that pollutants such as phthalates and bisphenol A disrupt DNA methylation at imprinted loci and modify sperm small RNA cargo [25]. Occupational exposures—including high temperatures, solvents, and radiation—further exacerbate oxidative stress during spermatogenesis.

Shi and Qi (2023) and Carter et al. (2023) both emphasize that such exposures often cluster with socioeconomic factors, complicating causal inference but reinforcing the need for a broader environmental perspective [23,26]

Paternal substance use introduces additional layers of epigenetic and oxidative stress. Alcohol consumption has been linked to altered sperm methylation patterns, increased DNA fragmentation, and disrupted chromatin packaging.

Although most studies focus on fertility outcomes rather than placental development, animal models suggest that paternal alcohol exposure impairs placental growth and fetal neurodevelopment. Nicotine exposure similarly alters sperm epigenetic markers and reduces sperm quality, while emerging evidence indicates that cannabis use modifies methylation at genes involved in neurodevelopment and metabolism.

These exposures likely interact synergistically with diet and physical activity, contributing to cumulative epigenetic load.

One of the most novel developments in paternal health research concerns the gut microbiome. Argaw-Denboba et al. (2024) demonstrated that perturbation of the paternal microbiome through antibiotic exposure altered sperm small RNA profiles and resulted in measurable changes in offspring growth and immune function [27].

While placental outcomes were not directly assessed, the systemic nature of microbiome-derived metabolites suggests plausible effects on placental development. Short-chain fatty acids, inflammatory mediators, and microbial metabolites can influence testicular epigenetic enzymes and endocrine signaling.

This work opens a new frontier in paternal research, positioning the microbiome as a mediator between lifestyle, diet, and germline programming.

Collectively, paternal physical activity and lifestyle factors influence placental development through overlapping pathways: endocrine regulation of spermatogenesis, oxidative stress and inflammatory signaling, epigenetic remodeling of sperm DNA and RNA, seminal plasma–mediated maternal immune adaptation, systemic metabolic and microbiome-derived signals.

The relative contribution of each pathway likely varies across individuals and contexts. Nonetheless, the convergence of evidence supports a central conclusion: paternal lifestyle before conception is biologically relevant, modifiable, and consequential for placental function and offspring health.

Biological Mechanisms Linking Paternal Factors to Placental Development

Understanding how paternal exposures translate into altered placental structure and function requires moving beyond associations toward mechanistic integration. The placenta does not respond directly to paternal behavior; rather, it is shaped by molecular signals transmitted at or around conception. These signals arise from the sperm cell itself, from seminal plasma, and from systemic paternal physiology interacting with the maternal reproductive environment.

What emerges from the literature is not a single dominant pathway, but a multi-layered biological cascade, in which epigenetic, metabolic, immunological, and endocrine mechanisms converge during the earliest stages of development.

DNA methylation remains the most extensively studied epigenetic mechanism linking paternal health to offspring outcomes. In sperm, methylation patterns reflect nutritional status, metabolic health, and environmental exposures accumulated during spermatogenesis.

Human studies provide compelling evidence that paternal obesity alters sperm methylation at developmentally relevant loci. Donkin et al. (2016) demonstrated genome-wide methylation changes in sperm from obese men, affecting genes involved in metabolism, neurodevelopment, and cellular growth [1]. Importantly, some of these loci overlap with genes expressed in the placenta, suggesting functional relevance beyond fertilization.

A critical subset of methylation-sensitive loci includes **imprinted genes**, many of which are paternally expressed and centrally involved in placental development. Soubry et al. (2019) showed that paternal obesity is associated with hypomethylation of the *IGF2* imprinting control region in newborns [2]. Given *IGF2*'s role in trophoblast proliferation and nutrient transport, altered imprinting provides a direct mechanistic bridge between paternal metabolic status and placental growth.

Animal models reinforce this link. Lambrot et al. (2013) and Morgan et al. (2021) demonstrated that paternal dietary imbalance—whether folate deficiency or low-protein intake—disrupts methylation at imprinting control regions and leads to abnormal placental development [12,18].

A recurring concern, however, is epigenetic reprogramming. Since most DNA methylation marks are erased after fertilization, critics argue that paternal methylation changes should not persist. Yet imprinting control regions are protected from demethylation, and even transient methylation differences during the earliest embryonic divisions may influence lineage allocation toward trophectoderm versus inner cell mass. Thus, methylation does not need to persist indefinitely to exert biological effects.

Small non-coding RNAs have emerged as one of the most persuasive mechanisms of paternal influence. Unlike DNA methylation, sperm small RNAs are not erased after fertilization and actively participate in early embryonic gene regulation.

Grandjean et al. (2015) provided experimental proof that sperm RNAs mediate the inheritance of diet-induced metabolic phenotypes [19]. Injection of sperm RNAs from obese males into

healthy zygotes was sufficient to reproduce metabolic dysfunction in offspring, implicating RNA cargo as a causal agent.

Zhang and Chen (2019) conceptualized this phenomenon as a "sperm RNA code," proposing that microRNAs and tRNA-derived fragments act as nutritional and metabolic sensors [9] These RNAs influence early transcriptional programs during zygotic genome activation, a period that precedes placental differentiation but sets its trajectory.

Evidence suggests that paternal exercise reshapes this RNA payload in beneficial ways. Costa-Júnior et al. (2021) showed that exercise-induced changes in sperm small RNAs improve offspring metabolic health [5]. Although placental endpoints were not the primary focus, altered early transcription almost certainly affects trophoblast differentiation.

The limitation of this literature lies in its translational gap. Most evidence derives from rodent models, and human validation remains limited. Nevertheless, the internal consistency of findings across dietary and activity-related exposures strengthens confidence in RNA-mediated mechanisms.

Contrary to earlier assumptions, sperm chromatin is not uniformly packaged by protamines. A small but functionally important fraction of histones is retained at promoters of genes involved in early development and placentation.

Houfflyn and Matthys (2017) argued that paternal obesity disrupts histone retention patterns and post-translational histone modifications, altering chromatin accessibility in the early embryo [15]. Similar observations have been reported in the context of poor diet and oxidative stress.

Histone marks such as H3K4me3 and H3K27me3 regulate gene activation and repression during embryogenesis. Disturbances in their placement may prime placental genes toward maladaptive expression profiles. While this mechanism is less studied than methylation or RNA signaling, it likely interacts synergistically with both.

One of the most conceptually important yet underappreciated pathways of paternal influence involves seminal plasma. Seminal plasma contains cytokines, prostaglandins, hormones, extracellular vesicles, and immune-modulatory factors that interact directly with the maternal reproductive tract.

Watkins et al. (2018) demonstrated that paternal diet alters seminal plasma composition in ways that impair maternal immune tolerance, disrupt implantation, and modify placental gene expression [11]. Notably, these effects occurred independently of sperm epigenetics, highlighting a parallel mechanism of paternal influence.

Khoshkerdar et al. (2021) extended this concept to humans, arguing that paternal metabolic and lifestyle factors influence maternal inflammatory status and uterine immune responses during early pregnancy [20]. Since placental development is highly sensitive to immune signaling during implantation, this pathway likely plays a critical role.

This literature challenges a sperm-centric view of paternal effects and has important methodological implications. Assisted reproduction techniques that remove seminal plasma may inadvertently obscure biologically relevant paternal signals.

Paternal metabolic health influences placental development not only through epigenetic marks but also via metabolic programming. Cechinel et al. (2022) demonstrated that paternal obesity induces mitochondrial dysfunction in offspring tissues, with early alterations detectable in the placenta [28].

Mitochondria regulate placental energy production, nutrient sensing, and hormone synthesis. Disruption of mitochondrial dynamics during early development may impair placental efficiency and constrain fetal growth.

Dimofski et al. (2021) further linked paternal nutritional stress to long-term metabolic disease in offspring, suggesting that placental dysfunction may represent an early bottleneck in this trajectory [29].

The paternal microbiome represents one of the newest mechanistic frontiers. Argaw-Denboba et al. (2024) showed that perturbation of the paternal gut microbiome alters sperm small RNA profiles and compromises offspring fitness [27].

Potential mechanisms include microbial metabolites influencing epigenetic enzymes, systemic inflammation affecting spermatogenesis, and microbiome-driven hormonal modulation. While direct placental measures were not assessed, the downstream developmental effects strongly implicate placental mediation.

This pathway underscores how diet, lifestyle, and environment converge at the level of systemic physiology before reaching the germline.

While individual studies often focus on isolated paternal exposures—such as obesity, micronutrient deficiency, or physical inactivity—emerging evidence suggests that paternal influences on placental development are best understood through an integrated mechanistic framework. Rather than acting through a single pathway, paternal factors converge across epigenetic, metabolic, endocrine, and immunological domains during the periconceptional period.

A comprehensive conceptual model linking paternal epigenetic alterations to placental health has been proposed by Bhadsavle and Golding (2022). In this framework, paternal environmental exposures modify the epigenetic architecture of the sperm, including DNA methylation, histone retention, and small non-coding RNA profiles.[30] These germline-derived signals are transmitted at fertilization and influence early embryonic gene regulation, particularly during zygotic genome activation. Subtle shifts at this stage may bias lineage allocation toward altered trophectoderm differentiation, with downstream consequences for placental structure and function.

Importantly, this model emphasizes that placental dysfunction does not arise solely from persistent epigenetic marks. Instead, transient epigenetic perturbations during early cleavage stages may be sufficient to alter trophoblast proliferation, angiogenic signaling, and nutrient transporter expression. Such effects align with experimental evidence showing placental hypoxia, impaired vascularization, and sex-specific placental adaptations following paternal metabolic stress, even in the absence of maternal pathology.

Bhadsavle and Golding further integrate seminal plasma–mediated pathways into this mechanistic landscape. Paternal lifestyle and diet influence the immunomodulatory composition of seminal plasma, shaping maternal immune tolerance and implantation dynamics.

These peri-implantation interactions provide an additional layer through which paternal signals can influence placental development independently of sperm-borne epigenetic information.

Finally, the model situates placental alterations within a broader developmental trajectory, linking early placental dysfunction to long-term offspring disease risk. Disrupted placental signaling may constrain fetal adaptive capacity, predisposing offspring to metabolic, cardiovascular, and neurodevelopmental disorders later in life. By positioning the placenta as a central mediator rather than a passive conduit, this integrated framework helps reconcile disparate findings across epidemiological, experimental, and mechanistic studies.

Taken together, the model proposed by Bhadsavle and Golding provides a unifying conceptual structure for interpreting paternal effects on placental health. It supports the central argument of this review: paternal preconception health shapes offspring outcomes not through a single dominant mechanism, but through a coordinated network of biological signals converging on placental development.

Conclusions, Limitations, and Future Directions

The accumulated evidence reviewed in this article challenges a long-standing assumption in reproductive science: that paternal influence on pregnancy outcomes ends at fertilization. Instead, data from human epidemiology, experimental animal models, and mechanistic epigenetic studies converge on a different conclusion. Paternal diet, physical activity, metabolic health, and lifestyle exposures shape the biological context in which placental development unfolds.

This influence is neither abstract nor indirect. It is encoded in sperm epigenetic architecture, mediated through seminal plasma signaling, and amplified during the earliest stages of embryogenesis. Studies consistently demonstrate that paternal obesity, poor dietary quality, micronutrient deficiencies, and chronic stress are associated with altered sperm DNA methylation [1], dysregulation of imprinted genes critical for placental growth [2], impaired placental vascularization [3], and increased risk of adverse pregnancy outcomes [7,8].

At the same time, the literature offers a more optimistic message: paternal health is modifiable. Exercise, balanced nutrition, and improved metabolic status can partially normalize germline signaling and improve offspring metabolic phenotypes [5,24]. These findings reposition fathers not as passive contributors but as active participants in developmental programming.

A key conceptual advance emerging from this review is the recognition of the placenta as a focal point of paternal influence. Although maternally supported, the placenta is genetically fetal and expresses a high proportion of paternally derived genes. As such, it is uniquely sensitive to paternal epigenetic disturbances.

Evidence indicates that paternal metabolic and nutritional stress can induce placental hypoxia, alter angiogenic signaling, and constrain nutrient transport capacity [3,28]. These placental alterations may act as early bottlenecks, shaping fetal growth trajectories and predisposing offspring to long-term metabolic disease [23,29].

Importantly, paternal influence on the placenta is not mediated solely by sperm. Seminal plasma—often overlooked in reproductive research—has emerged as a critical signaling interface. Paternal diet and lifestyle modify seminal plasma composition in ways that influence

maternal immune tolerance and implantation success [11, 20]. This expands the biological window of paternal influence to include peri-implantation maternal–paternal interactions.

From a sport science perspective, the findings reviewed here carry important implications. Physically active men and athletes often experience unique physiological states characterized by fluctuating energy availability, elevated oxidative stress, and hormonal adaptations. While regular moderate exercise appears beneficial for sperm epigenetic integrity and offspring metabolic health [5], excessive training loads or chronic energy deficiency may introduce opposing stressors.

The current literature does not yet distinguish clearly between adaptive and maladaptive exercise thresholds in the context of paternal programming. However, the evidence strongly suggests that preconception guidance for men—particularly athletes—should integrate training load management, nutritional adequacy, recovery, and stress reduction.

Despite rapid progress, several limitations constrain interpretation of the current evidence.

First, animal models dominate mechanistic research. While rodent studies offer experimental control and biological insight, placental structure and trophoblast invasion differ substantially between species. Sheep models [31] offer improved translational relevance, but human placental data remain limited.

Second, human studies are largely observational. Paternal and maternal exposures frequently co-occur, making it difficult to isolate independent paternal effects. Residual confounding remains a persistent challenge, particularly in studies relying on self-reported lifestyle data.

Third, epigenetic causality is difficult to establish. While associations between paternal exposures and sperm epigenetic marks are robust, demonstrating that specific epigenetic modifications directly cause placental dysfunction remains complex. Small RNA studies provide strong experimental evidence [19,9], but human validation is still scarce.

Finally, placental outcomes are underreported. Many studies infer placental involvement indirectly through offspring phenotypes, rather than measuring placental structure, gene expression, or vascularization directly.

Future research should aim to move the field from association to application. Several priorities emerge:

1. Paternal-focused intervention studies, assessing the impact of diet, exercise, and micronutrient optimization across a full spermatogenic cycle.

2. Integrated multi-omics approaches, combining sperm methylation, small RNA profiling, histone mapping, and seminal plasma proteomics.

3. Direct placental phenotyping in human studies, including vascular, metabolic, and immunological markers.

4. Sport-specific investigations, examining how training intensity, recovery, and energy availability influence paternal germline signaling.

5. Microbiome-centered research, exploring how diet–microbiome interactions shape sperm epigenetics and early placental programming [27].

Equally important is the translation of this evidence into balanced public health messaging. Emphasizing paternal responsibility must avoid moralization or blame. Instead, the goal should be empowerment through evidence-based guidance.

The evidence reviewed here supports a fundamental shift in how paternal biology is understood within reproductive science. Fathers contribute more than genetic material; they contribute a biological narrative shaped by diet, activity, and environment. This narrative is read by the early embryo and written into placental structure and function.

Recognizing paternal preconception health as a modifiable determinant of developmental outcomes not only advances scientific understanding but also opens new avenues for prevention, intervention, and interdisciplinary collaboration—particularly at the intersection of reproductive biology and sport science.

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