Different Exercises, Glucose Homeostasis and Ayurveda Perspectives

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Abstract: ***Glucose homeostasis is tightly regulated by hormonal and cellular pathways, particularly insulin-mediated glucose uptake, hepatic glucose output, and skeletal muscle metabolism. Physical exercise induces robust physiological adaptations that enhance insulin sensitivity through AMPK and IRS-Akt signaling, GLUT4 translocation, mitochondrial biogenesis, and improved β-cell function. Aerobic, resistance, and high-intensity interval training (HIIT) differentially modulate these mechanisms, with combined training showing superior effects on glycemic indices and metabolic flexibility. Ayurvedic physiology conceptualizes glucose imbalance as dysfunction of Agni, Meda Dhatu (adipose tissue), and obstructed Srotas (transport pathways). Interventions like Vyayama (exercise), Swedana (sudation), and Udvartana enhance tissue perfusion, reduce oxidative stress, and improve cellular glucose handling-paralleling established physiological mechanisms. Understanding these exercise-induced adaptations through both modern and traditional lenses reveals converging pathways in metabolic regulation. An integrated, physiology-based approach may enhance therapeutic strategies for insulin resistance and type 2 diabetes.***

Keywords: Glucose homeostasis, Insulin signaling, Exercise physiology, AMPK, GLUT4, Mitochondria, Ayurveda, Meda Dhatu, Agni

1. Introduction

Glucose homeostasis is a complex physiological process essential for sustaining energy supply to metabolically active tissues, particularly the brain and skeletal muscles. This balance is maintained through an intricate interplay of hormonal signals—primarily insulin and counter-regulatory hormones like glucagon and cortisol governing hepatic glucose production and peripheral uptake [1,2]

Exercise significantly modulates glucose metabolism via distinct molecular mechanisms.Aerobic training enhances glucose uptake independent of insulin through muscle contraction-induced GLUT4 translocation, largely mediated by AMPK and PGC-1α pathways [3,4] Resistance training improves glucose disposal by increasing muscle mass and insulin sensitivity via modulation of IRS-Akt signaling [5] Additionally, HIIT promotes rapid glycogen turnover, mitochondrial biogenesis, and favorable adipokine profiles, contributing to improved insulin action in both healthy and insulin-resistant individuals [6].

In the Ayurvedic framework, metabolic function is governed by Agni, the biological fire responsible for transformation at cellular and systemic levels. Physical activity (Vyayama) is emphasized for stimulating Agni, reducing Meda Dhatu (adipose tissue), and maintaining systemic homeostasis. Interventions like Udwartana and Swedana are traditionally used to mobilize fat and enhance physiological circulation, akin to promoting capillary perfusion and metabolic clearance in modern terms [7,8].

Moreover, the concept of Srotas—microchannels responsible for nutrient transport—aligns with vascular and endocrine signaling pathways. Disruption in these channels is considered analogous to modern concepts of endothelial dysfunction and impaired intercellular communication. Ayurvedic practices such as Yogasana and Pranayama are believed to protect Srotas, regulate the HPA axis, and mitigate oxidative stress—mechanisms increasingly validated in metabolic research [9,10].

This review synthesizes modern and Ayurvedic insights to evaluate how various exercise modalities influence glucose metabolism and metabolic health.

2. Methodology

Physical exercise constitutes a critical physiological stimulus capable of modulating glucose homeostasis through complex, integrated mechanisms involving skeletal muscle glucose uptake, insulin signaling pathways, hepatic glucose output, and pancreatic β-cell function. These adaptations occur both acutely -during and immediately following exercise and chronically, as a result of repeated training stimuli. Importantly, the metabolic outcomes of exercise are not uniform; rather, they are highly contingent upon the specific modality, intensity, and duration of the physical activity undertaken. Consequently, delineating the mechanistic differences among various exercise types is essential to understanding their distinct roles in the regulation of glucose metabolism and the prevention or management of dysglycemic states.

Types of Exercise and Glucose Homeostasis

Physical exercise elicits potent metabolic responses that enhance glucose homeostasis through insulin-independent and insulin-mediated pathways. However, the specific effects vary based on the modality, intensity, and duration of the exercise performed. The following section delineates the physiological and molecular effects of different exercise types on glucose regulation.

1) Aerobic (Endurance) Exercise

Aerobic exercise is characterized by prolonged, rhythmic activity engaging large muscle groups. During such exercise, skeletal muscle contractions stimulate glucose uptake via insulin-independent mechanisms, primarily through the translocation of glucose transporter type 4 (GLUT4) to the sarcolemma, mediated by AMP-activated protein kinase (AMPK) and Ca^{2+}/calmodulin-dependent protein kinases [11,12]. Chronic aerobic training enhances insulin sensitivity through improved insulin receptor signaling, upregulation of PI3K-Akt pathways, and increased GLUT4 expression [13].

Additionally, aerobic exercise suppresses hepatic glucose production under hyperinsulinemic conditions by improving hepatic insulin sensitivity [14]. In animal models, endurance training promotes pancreatic β-cell survival and proliferation via IGF-1/IRS2/Akt signaling, supporting enhanced glucose-stimulated insulin secretion [15]. Nevertheless, the insulin-sensitizing effects of aerobic activity tend to wane within 48–72 hours of inactivity, emphasizing the need for regular training [16].

2) Resistance (Strength) Training

Resistance exercise involves repeated bouts of muscle contractions against external resistance, which induces hypertrophy and increases muscle cross-sectional area, thereby expanding glucose storage capacity (17). Resistance training improves insulin action both by increasing muscle mass and by enhancing muscle insulin signaling pathways.

Moreover, in human and animal models, resistance exercise has been shown to improve pancreatic β-cell function. Rodents subjected to resistance training displayed elevated insulin secretion, reduced endoplasmic reticulum (ER) stress markers, and increased expression of glucose-sensing genes such as GLUT2 and glucokinase in pancreatic islets [18,19]. In vitro studies using serum from resistance-trained mice demonstrated reduced β-cell apoptosis and enhanced survival under pro inflammatory conditions [20].

In clinical populations, resistance training can improve glucose tolerance and insulin sensitivity, particularly when combined with dietary management. However, factors such as macronutrient intake and baseline insulin resistance modulate the extent of metabolic benefits [21].

3) High-Intensity Interval Training (HIIT)

HIIT consists of alternating bouts of intense anaerobic effort with recovery periods. This modality produces robust metabolic adaptations in a time-efficient manner. Mechanistically, HIIT activates multiple glucose regulatory pathways, including AMPK and mitogen-activated protein kinases (MAPKs), leading to increased GLUT4 translocation and mitochondrial biogenesis [22].

Compared to moderate continuous training, HIIT elicits comparable or greater improvements in insulin sensitivity and glycemic control, particularly in individuals with impaired glucose tolerance [23]. The post-exercise period is marked by elevated oxygen consumption (EPOC), further enhancing glucose utilization in the recovery phase.

4) Combined (Concurrent) Training

Concurrent training integrates both aerobic and resistance modalities within a single program. This approach has demonstrated synergistic effects on glucose homeostasis. Aerobic components improve mitochondrial oxidative capacity and insulin sensitivity, while resistance elements expand lean muscle mass and augment glucose disposal potential [24].

Clinical trials have shown that combined training leads to greater reductions in HbA1c, fasting glucose, and insulin resistance indices compared to either modality alone. This effect is attributed to broad molecular adaptations across skeletal muscle, liver, and adipose tissues, as well as favorable changes in inflammatory and oxidative stress markers [25].

5) Alternative Modalities and Special Populations

In older adults with sarcopenia or mobility limitations, elastic resistance training has emerged as a feasible and effective intervention. A randomized controlled trial demonstrated that 12 weeks of elastic band resistance training significantly improved glucose tolerance, insulin sensitivity (as measured by HOMA-IR), and muscle function in older individuals with sarcopenic obesity [26].

Additionally, prolonged low-intensity endurance activities promote glucose homeostasis by enhancing hepatic glucose output regulation, increasing fat oxidation, and improving metabolic flexibility, particularly during extended exercise bouts [27].

Exercises and Mechanism cellular pathway:

Exercise Type	Target Tissue / Cell	Mechanism Cellular Pathway	References
Aerobic (Endurance)	Skeletal muscle, liver,adipose tissue	↑ GLUT4 translocation via AMPK activation; ↑ mitochondrial biogenesis; ↑ capillary density; ↓ hepatic glucose output	(30,33,34)
Resistance Training (RT)	Skeletal muscle (type II fibers) adipose tissue	↑ Muscle mass → ↑ glucose uptake; ↑ IRS-1/Akt signaling; ↑ glycogen synthase; ↓ lipotoxicity	(33, 34)
High-Intensity Interval Training (HIIT)	Skeletal muscle, liver	↑ AMPK and p38 MAPK activation; ↑ GLUT4 translocation; ↑ mitochondrial density/function; ↓ insulin resistance	(28, 29, 31)
Combined (Aerobic + Resistance)	Skeletal muscle, liver, adipose tissue	oxidative + hypertrophic adaptation; ↑ insulin signaling; ↓ inflammation; ↑ total glucose disposal	(33, 35)

Exercise and its metabolic effects:

Exercise type	HbA1c Reduction	Fasting Glucose	Insulin Sensitivity (HOMA-IR)	Time Efficiency	Additional Notes	References
Aerobic Training	↓~0.5-0.7%	↓10-20mg/dL	↑↑ (moderate improvement)	Moderate (>150 min/week)	Improves VO2 max, lipid profile, and BP	(36-38)
Resistance Training (RT)	↓~0.3-0.6%	↓8-15 mg/dL	↑↑↑ (especially in obese/T20)	Moderate (2-3x/week)	Enhances lean mass; beneficial in elderly populations	(39-41)
Combined AT + RT	↓~0.8-1.2%	↓>20 mg/dL	↑↑↑↑ (Best Overall)	High (more time required)	Most effective for T2DM and metabolic syndrome	(42,43)
High-Intensity Interval Training (HIIT)	↓~0.7-1.0% (short duration)	↓10-20 mg/dL	↑↑↑ (rapid but may be transient)	Very High (15-30 min. 3x/week)	Rapid insulin sensitivity-gains boosts cardiorespiratory fitness	(44-46)
Flexibility/Balance Training	Minimal direct effect	Minimal direct effect	Indirect (via stress/ cortisol)	Low	Enhances mobility: reduces fall risk complements other forms	(47)

[Abbreviations: ↑ = mild improvement; ↑↑ = moderate; ↑↑↑ = strong; ↑↑↑↑ = very strong, HbA1c = Glycated Hemoglobin, HOMA-IR = Homeostasis Model Assessment of Insulin Resistance, VO_2max = Maximal oxygen consumption, BP = Blood Pressure, T2DM = Type 2 Diabetes Mellitus, MetS = Metabolic Syndrome]

Ayurvedic Physiological Perspective on Glucose Regulation and Metabolic Modulation

From the lens of Ayurvedic physiology, regulation of glucose and lipid metabolism is governed by the balance of doshas, primarily Kapha and Vata, the functional integrity of Meda dhatu, and the robustness of Agni (digestive and tissue-level metabolism). Disturbances in these factors may lead to an accumulation of metabolic byproducts (Ama), sluggishness in transport systems (Srotorodha), and impaired nutrient utilization features conceptually aligned with deregulated glucose homeostasis in modern physiology.

Several classical interventions support the restoration of Agni, clearing of Srotas, mobilization of excess Meda, and recalibration of dosha balance - all of which influence systemic metabolic responses.

1) Vyayama (Physical Activity)

Regular, appropriate physical activity is emphasized in classical physiology for maintaining the balance of Kapha and promoting Meda kshaya (adipose modulation). Vyayama enhances Agni, clears srotas, and induces laghutva (lightness) and sthiryata (stability). Physiologically, these effects correspond to increased skeletal muscle glucose uptake, improved insulin receptor sensitivity, and enhanced GLUT-4 expression. Additionally, yyayama reduces systemic inflammation and improves mitochondrial efficiency, facilitating better metabolic control (48,49).

2) Abhyanga (Oil Massage)

Abhyanga, with oils prepared using Kapha-Meda-pacifying herbs, aids in restoring snigdhatva (unctuousness) and vata-samana, while simultaneously promoting circulatory and lymphatic stimulation. From a physiological standpoint, Abhyanga has been associated with reduced sympathetic over activity, improved micro vascular perfusion, and lower cortisol levels - thereby reducing the burden on glucose regulatory mechanisms and improving tissue responsiveness to insulin (50).

3) Udvartana

Udvartana is performed with dry, penetrating herbs and is aimed at reducing the excessive snigdhata and sthira guna associated with Meda. It facilitates Rasa-Rakta-movement, promotes Srotoshuddhi, and induces Rukshata (dryness) to counterbalance aggravated Kapha and Meda. Mechanistically, Udvartana has been shown to enhance lipid metabolism, reduce adipocyte hypertrophy, and improve tissue insulin responsiveness through better vascular and interstitial dynamics (51).

4) Swedana (Sudation Therapy)

Swedana promotes Ama pachana and srotoshodhana, facilitating unobstructed movement of Rasa and Rakta and enhancing tissue-level exchange. It also induces vasodilation, improves interstitial fluid turnover, and reduces viscous stagnation within microchannels. Modern evidence supports that Swedana elevates heat shock proteins (HSPs), reduces oxidative stress, and promotes insulin signalling pathways, thereby assisting in metabolic regulation (52).

5) Mardana (Deep Tissue Manipulation)

Mardana, a deeper and more vigorous tissue manipulation than Abhyanga, is employed to mobilize stagnant Kapha and Meda at a deeper dhatu level. It enhances prabhava (functional potency) of the tissues, stimulates mamsa and meda dhatvagni, and increases tissue receptivity. Physiologically, this mirrors enhanced blood flow, mechanical stimulation of adipocytes, and deep tissue perfusion, all contributing to improved metabolic turnover and glucose uptake (53).

6) Padabhyanga (Foot Stimulation Therapy)

Padabhyanga exerts its effects through marma stimulation, influencing vyana vata and promoting neurological balance.It has a calming effect on manovaha srotas and autonomic modulation via peripheral afferents. Modern studies suggest it improves heart rate variability (HRV) and reduces sympathetic hyperactivity, which is beneficial for neuroendocrine regulation of glucose metabolism under stress (54).

Ayurvedic interventions and metabolic effects

Intervention	Ayurvedic Physiological Action	Modern Physiological Correlate
Vyayama	Agni deepana. Meda kshaya, Srotoshuddhi	↑ GLUT-4, ↑ Insulin sensitivity, ↓Visceral fat
Abhyanga	Kapha-vata shamana, Srotas vivechana	↓ Cortisol, ↑ Microcirculation, ↑ Parasympathetic tone
Udvartana	Rukshana. Meda lekhan. Srotoshodhana	↑ Lipolysis, ↓ Central adiposity, ↑ Insulin responsiveness
Swedana	Ama pachana,Srotoshodhana, Agni vardhana	↓ Oxidative stress. ↑ Glucose trafisport
Mardana	Dhatvagni stimulation	↑ Deep tissue perfusion, ↑Metabolic turnover
Padabhyanga	Vata shaman,Marma stimulation,Manovaha srotas poshana.	↓ Autonomic stress. ↑Glycemic control

3. Discussion

Glucose metabolism is regulated by complex hormonal, cellular, and systemic factors. Insulin sensitivity, mitochondrial function, inflammation control, and neuroendocrine balance are critical for maintaining glucose homeostasis and preventing diabetes. Exercise improves these parameters, with combined aerobic and resistance training offering superior benefits in glucose uptake and metabolic flexibility over either type alone.

Ayurveda views glucose regulation as a balance of Agni (digestive fire), Doshas (bioenergetic forces), Dhatus (tissues), and Srotas (channels). Impaired Agni leads to Ama (toxins) and Srotorodha (blockages), comparable to oxidative stress and insulin resistance. Meda Dhatu (fat tissue) plays a key role in metabolic imbalance. Ayurvedic therapies like Vyayama (exercise), Abhyanga, and Swedana restore Agni, clear channels, and balance Doshas, supporting metabolic health.

Integrating Ayurveda's holistic approach with modern biomedical insights offers a comprehensive framework for managing glucose metabolism. A personalized combination of aerobic and resistance exercises aligns with both systems, promoting optimal metabolic function and overall balance.

4. Conclusion

Glucose metabolism is regulated through complex hormonal, cellular, and systemic interactions. Key factors include insulin sensitivity, mitochondrial efficiency, inflammation control, and neuroendocrine regulation. Both aerobic and resistance exercises enhance these mechanisms, but combined training yields greater improvements in glycemic control, muscle glucose uptake, and metabolic flexibility. Aerobic exercise primarily improves cardiovascular health and mitochondrial function, while resistance training increases muscle mass and GLUT4-mediated glucose transport.

From an Ayurvedic perspective, glucose homeostasis depends on the balance of Agni (metabolic fire), Doshas (bioenergetic forces), Dhatus (tissues), and Srotas (channels). Disruption of Agni leads to Ama (toxins) and Srotorodha (blockages), analogous to oxidative stress and insulin resistance. Meda Dhatu (adipose tissue) plays a central role in these metabolic disturbances. Ayurvedic interventions, including Vyayama (exercise) and therapies like Abhyanga and Swedana, restore metabolic fire, clear channels, and reduce Kapha-Meda imbalance, thereby improving glucose metabolism and mitochondrial function.

Integrating Ayurveda's holistic framework with contemporary biomedical knowledge offers a comprehensive approach to managing glucose metabolism. Personalized, combined aerobic and resistance training aligns with both paradigms, optimizing metabolic health and systemic balance.

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