FLUORIDE

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A Systematic Review of Fluoride Consumption and Its Impact on Sports Performance: Potential Implications for Fundamental Motor Skills Development and Precision Movement

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ABSTRACT

Background: Fluoride disrupts calcium signaling and mitochondrial function, leading to impaired muscle contractility, reduced endurance, and diminished precision. When compared to athletes in nonfluroide regions, athletes and youth in fluoride endemic regions also suffer disproportionate adverse effects, involving strength, endurance and movement based on precision, because of their high water intake and developmental vulnerabilities.

Objectives: To undertake a systematic review of the effects of fluoride exposure on neuromuscular function, motor skill development, and sports performance, with a particular emphasis on strength, endurance, and precision based movements.

Methods: Fifty two studies from PubMed, Scopus and Web of Science (2000–2023) were reviewed using PRISMA guidelines. Studies that examined the impact fluoride had on the neuromuscular function and athletic performance of human and animal were inclusion criteria. Quantitatively and qualitatively the data were synthesized.

Results: The disrupted signaling of calcium by fluoride diminishes muscle contractility, reduces endurance, and diminishes overall precision. The children exposed to high fluoride levels actually had a 20 % decline in grip strength, slower reaction times, and reduced VO_2 max. Children in fluoride endemics regions like Sindh, Pakistan presented delayed motor milestones and neuromuscular deficits.

Conclusions: Motor function as well as athletic performance is dramatically affected by exposure to excessive fluoride. These effects can be mitigated by interventions, including de-fluoridation technologies and nutritional strategies. The long term outcomes and mitigation measures need to be further researched.

Keywords: *Fluoride, Neuromuscular Function, Motor Skills, Sports Performance, Endemic Fluorosis*

1. INTRODUCTION

Fluoride, an element which naturally exists in water, soil, and many dietary sources has been well known for its importance in dental and skeletal health for many years. Water fluoridation, toothpaste and supplements have all been hyped as the systemic introduction of fluoride, and have been credited with reducing dental caries and improving overall oral health throughout the world. Despite its benefits, fluoride has been the subject of growing concern for a variety of reasons — as it has systemic effects, including as it is consumed in excess [1]. The neurotoxic, musculoskeletal and cognitive effects of fluoride exposure at elevated levels, as revealed by recent studies, raise questions regarding broader implications for human health and performance. In particular, but not limited to, these have received a fair amount of interest in connection with sports science considerations, where sport specific motor skills, coordination and performance are of utmost importance[2].

Success in athletic performance has to do with precision, strength, endurance and neuromuscular coordination. Because these attributes result from the delicate interplay of physical and cognitive functions, athletes are highly susceptible to disruptions by systemic agents such as fluoride. Due to the great volumes of water consumed by athletes in preparation and competition, the fluoride exposure of athletes is often large and may be magnified, especially in areas where there is high ground water fluoride [3]. The additional attention to the issue of fluoride and its potential unintended detrimental effects on athletic performance has created worry that fluoride may be detrimentally affecting athletic performance, for instance in those equestrian and athletic sports that require fine motor skill and precision movements.

To countries such as Pakistan, where high levels of fluoride in groundwater have been routinely reported, the problem of excessive fluoride exposure is particularly significant. Groundwater fluoride concentrations are often above the World Health Organization (WHO) recommended limit of 1.5 mg/L in Sindh, Punjab and Khyber Pakhtunkhwa. Most of this is due to the geological characteristics of the region that allows fluoride to leached into water sources [4]. As a result it puts in excess millions of Pakistanis drinking water at risk of fluorosis and other systemic health effects. The dental and skeletal effects of fluoride are well known in Pakistan, but its effects on neuromuscular function, cognition and sports performance are not.

This is a challenge for athletes in Pakistan, especially those training in fluoride endemic areas. The hot climate in the country makes it necessary for athletes to take in more water to stay hydrated, and that's compounded by fluoride exposure. Particularly at risk are youth athletes, who are undergoing critical stages of physical and neuromuscular development, to the adverse effects of fluoride. If chronic exposure occurs during these developmental periods, they may impair motor skill acquisition and delay milestones underlying the acquisition of basic foundational motor skills such as running, jumping and coordination. The motor skills learned through these exercises are fundamental skills needed to advance to more technical sports and there they have to be controlled with increased precision and also need advanced motor control.

Several physiological pathways mediate the effects of fluoride on motor functions. Fluoride is known to disrupt calcium signaling, an integral part of neuromuscular transmission and muscle contraction. Excessive fluoride is connected to mitochondrial dysfunction, oxidative stress and structural changes in bone and muscle tissues [5, 6]. And that has an impact on your athletic performance — reduced muscle strength, slower response time, poor coordination. Additionally, fluoride has been shown to have the potential to be a neurotoxin, including the ability to accumulate in the brain, and its potential effect on athletes, in terms of its ability to cause cognitive impairment and deficits in motor control, is further heightened.

Though the risks are more widely recognized, fluoride consumption and sports performance is an untested relationship. Although many studies have been made on the impact of blood ingestion (fluoride) on dental and skeletal health, very few studies have been conducted on the widespread systemic effects, including its implication for neuromuscular and motor functions of the athletes. Unfortunately, studies to this point have been fragmented, analyzing only select aspects of fluoride exposure, instead of capturing the full picture of its effect on sports performance. This lack of clarity, however, is a crucial gap in the literature, especially in countries like Pakistan where fluoride exposure remains a major public health problem that requires a systematic review of evidence.

To explore the relationship between fluoride consumption and sports performance comprehensively, this review addresses the following key research questions:

What does fluoride consumption do to neuromuscular function and motor skills in athletes and youth?

To what extent does excessive fluoride exposure impact sports performance specifically in terms of strength, endurance and precision-based movement?

This systematic review seeks to synthesize and evaluate the available evidence on the relation between sports performance and fluoride consumption in relation to the effects fluoride consumption has on neuromuscular function, motor skill development and precision-based movements. This review integrates findings from a diverse set of studies to understand the physiological mechanisms by which fluoride disrupts athletic performance and skill acquisition. It also seeks to expose the risks involved in ingesting more fluoride than what is healthy for professional athletes and developing youth populations and offers open ideas to reduce these risks. It concludes with the gaps in the current literature, and suggested directions for future research that aim to further enhance our understanding of and inform public health and sports training strategies. This review adds to a global understanding of fluoride and its impact on health and athletic performance by addressing the unique challenges encountered in fluoridation PRs such as Pakistan.

2. LITERATURE REVIEW

The systemmatic effects of Fluoride have been studied in depth, with emphasis to dental and skeletal health. Yet increasingly, its influence on neuromuscular function, motor skills, and sports performance is of interest to athletes and youth populations. In this section findings from key studies are synthesized to demonstrate fluoride's physiological effects and its potential to hinder athletic performance and motor development.

2.1 FLUORIDE AND NEUROMUSCULAR FUNCTION

Interference with calcium homeostasis and disruption of processes related to muscle contraction are the bases for fluoride's effects on neuromuscular function. Synaptic transmission, as well as excitation-contraction coupling in muscle fibers, is highly calcium dependent. Furthermore, the excess fluoride inhibits calcium ion channels which reduces muscle contractility, and slows reaction times [7]. Studies in animals have repeatedly shown that, at high concentrations, fluoride is harmful to motor coordination. For example, assay of the motor coordination and nerve conduction velocities of rodent models exposed to higher than 2 ppm fluoride resulted in reduced velocity and impaired coordination [8].

Excessive fluoride exposure has been also associated with neuromuscular deficiencies in human populations. In a study by Singh, Rishi [9] of athletes from fluoride endemic regions of India, grip strength and performance on balance were significantly less than athletes in non endemic regions. As with Lee, Hong [10] fluoride levels over 2 ppm were associated with decreased response times and decreased agility among a cohort of professional soccer players. The findings indicate that fluoride may slow the responses that are critical for athletic performance, such as rapid neuromuscular results.

2.2 FLUORIDE AND MOTOR SKILL DEVELOPS

In children, motor skill development is highly sensitive to systemic disruption. The use of precise coordination between neuromuscular and cognitive systems is critical for fundamental motor skills, including running, jumping, throwing, and early coordinated behaviors, which also address fundamental concepts in the study of cognitive and social development of children. Delay in motor milestones and impairment of hand eye coordination has been observed when there is chronic exposure to fluoride during critical developmental periods. Longitudinal study by Patel, Das [11] using 300 children exposed to fluoride concentration above 1.5 ppm compared with low fluoride children in Pakistan showed significantly lower scores of motor skill assessment.

Fluoride has been implicated as the cause of these neurotoxic developmental delays. This fluorine accumulates in regions like the cerebellum which is so important for motor control and coordination [12]. Children exposed to high fluoride levels have shown reduced activation in motor regions of the brain during functional MRI studies of task coordination. These are unpleasant findings, and it remains to be seen if these early motor skill deficits indeed have lasting consequences for sports performance and other areas of physical competence.

2.3 FLUORIDE AND SPORTS PERFORMANCE

Because athletes drink more water to stay hydrated during training and competition, athletes are especially sensitive to fluoride exposure. Excessive fluoride levels may negatively affect endurance, strength, and precision movement component of the sport performance. Kumar, Goswami [13] examined cyclists who live in areas that have high fluoride concentrations in their drinking water and found a 12 per cent reduction in VO_2 max, a gauge of aerobic capacity. The fluoride exposure was proposed to induce mitochondrial dysfunction, resulting in a decrease of energy metabolism and early fatigue, which was attributed to this reduction.

Studies on weightlifters and sprinters have shown that fluoride also impacts strength and power. Muscle contractility interference has been linked to excessive fluoride exposure leading to diminished grip strength and reduced anaerobic performance [14]. Fluoride's neurotoxicity is particularly harmful in cases where precision movements are needed, like athletics like gymnastics or archery. In gymnasts, fluoride levels in excess of 2 ppm resulted in significantly poorer balance and precision performance compared to lower fluoride exposed gymnasts [15].

2.4 EVIDENCE FROM PAKISTAN

High natural fluoride levels in groundwater ramp up these concerns in Pakistan. Ahmad, Singh [16] found in a study of Sindh that drinking water was often fluoridated above 3 ppm, with high prevalence of skeletal and dental fluorosis among its residents. In these athletes and children, fluoride induced neuromuscular impairments and motor skill deficits are prevalent. These findings emphasize the need for dedicated interventions to reduce fluoride exposure in high risk population. The detail insights of the fluoride studies related to the health concerns are discussed below.

Table 1: Key insights of Fluoride impact on health

Study	Population	Fluoride Level (ppm)	Outcome	Key Findings
[17]	Rodent models	>2 ppm	Neuromuscular function	Reduced nerve conduction velocities and impaired motor coordination.
[9]	Athletes in India	1.5–3 ppm	Strength, balance	Significant reduction in grip strength and balance performance.
[10]	Soccer players	>2 ppm	Reaction time, agility	Delayed reaction times and decreased agility in fluoride-exposed athletes.
[18]	Children in Pakistan	>1.5 ppm	Motor skill development	Delayed motor milestones and lower motor skill scores in fluoride-endemic areas.
[13]	Cyclists	2–4 ppm	Endurance (VO_2 max)	12% reduction in VO_2 max due to mitochondrial dysfunction.
[15]	Gymnasts	>2 ppm	Precision movements	Poorer performance in balance and precision tasks among fluoride-exposed athletes.
[16]	Residents in Sindh, Pakistan	>3 ppm	Skeletal and neuromuscular health	High prevalence of fluorosis and impaired neuromuscular function.

2.5. KEY INSIGHTS:

Neuromuscular Function: Wu, Wang [17] as well as Ahmad, Singh [16] reveal that fluoride disturbs neuronal coordination and muscle coordination resulting in decreased neuromuscular efficiency.

Motor Skills Development: Research such as Baboo, Patel [18] attracts attention to how chronic fluoride exposure delays motor milestones in children and puts the risk ahead of critical developmental periods.

Sports Performance: Lee, Hong [10] and Kumar, Goswami [13] found that the exposure of fluoride impacts reaction times, endurance and agility, all of which are important to athletic success.

Precision Movements: As noted in Xu, Bian [15] fluoride's neurotoxicity impairs the fine motor control needed for sports that depend upon balance and precision.

This work shows fluoride to have a multifaceted effect, a finding particularly highlighted in high exposure environments such as Pakistan and other areas affected by fluoride. The need for additional research and directed interventions is highlighted by these findings.

This review demonstrates that fluoride is a multistranded factor affecting neuromuscular function, motor skills, and sports performance. The findings underscore the need to consider fluoride exposure, in part because natural fluoride levels often exceed safe limits in places such as Pakistan. The insights provided the basis for practical recommendations to reduce risk associated with fluoride in athletic and developmental contexts.

3. METHODS

This systematic review was carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, following guidelines for transparency and methodological rigour. A review was conducted to identify peer reviewed studies examining the relationship between fluoride exposure, sports performance, neuromuscular function, and motor skill. To achieve this, a comprehensive search strategy was employed across three major databases: Web of Science, PubMed and Scopus. The databases chosen for their full coverage of biomedical, sports science, and toxicological literature. Search terms included combinations of keywords and Boolean operators including "fluoride AND sports performance", "fluoride AND motor skills", "fluoride AND precision movement", and "neuromuscular function AND fluoride". To remain relevant to the search results, articles were filtered to examine only studies published between January 2000 and March 2023 and limited to articles in English.

The inclusion and exclusion criteria were defined very carefully so that studies that specifically address the objectives of the review are included and others excluded [19]. Studies of human or animal populations exposed to fluoride through drinking water, diet or other environmental sources in which data concerning neuromuscular function, motor skills, or sports performance could be found were included. Endurance, strength, agility, coordination and reaction time were considered eligible outcomes. They included cross-sectional, cohort, case control, experimental and intervention studies, with clearly defined methods. Studies which considered only dental or skeletal health without evaluation of neuromuscular or motor outcomes were excluded [20]. Analysis did not include reviews, editorials, commentaries, or conference abstracts that lack original data, or non peer-reviewed articles. However, articles were excluded if fluoride exposure levels were not quantified or specified.

The screening and selection process followed PRISMA guidelines, consisting of three primary phases: screening and eligibility assessment, and identification. Of these 1,200 articles are were found across all three databases. In total, after removing 250 duplicate entries using EndNote software, we were left with 950 unique articles to read further. Articles titles and abstracts were screened independently by two reviewers to determine relevance for research questions. A detailed full text review of 370 articles remained. This process excluded 580 articles that did not meet the inclusion criteria. During the full text review phase, another 318 articles were excluded; they were not relevant to sports performance, did not have relevant outcomes, did not have sufficient fluoride exposure data, or were otherwise excluded. In the end 52 eligible studies were included in the final analysis.

A standardized data extraction form was used to extract data from the included studies in order to ensure consistency and accuracy [20]. Main characteristics of studies (author, year of publication, and study design) and of populations (age, sex, and fluoride exposure levels), measured outcomes (motor skill performance, neuro muscular function, sports metrics like VO_2 max or grip strength), and the main findings were recorded. Reliability of the findings from the studies were also assessed for methodological quality. Evaluation of observational studies was performed using Newcastle-Ottawa Scale and experimental studies with Cochrane Risk of Bias Tool. The validity of the review was maintained by excluding studies deemed to be at a high risk of bias.

The extracted data was synthesized using quantitative and qualitative approach. Using RevMan software, pooled effect sizes and confidence intervals of similar studies were calculated for outcomes such as grip strength or endurance (VO_2 max). Thematic analysis was used for studies with divergent or multiple methodology or outcomes, for example identifying common patterns and themes about fluoride and coordination, or fluoride and cognitive motor integration. The collective results were a complete look at the dichotomous relationship between fluorine exposure and sports."The graphiochal representation of the studies selected for theis systematich review is presented in figure 1.

We present the study selection process using the PRISMA flow diagram that summarises each stage of the review. The first search turned up 1,200 records, 250 of which were duplicates, which we then reduced to 950 articles for screening. 580 articles were excluded following title and abstract screening, 370 were evaluated in full text. Of these 318, 52 studies were included in this review, as others were not relevant, or their limitations deemed irrecoverable, leaving 318 excluded. The approach of this review guarantees that the evidence collected on which the findings of this review are based meet the requirements of systematic and transparent, as well as accurate and reliable, and hence relevant to the research question.

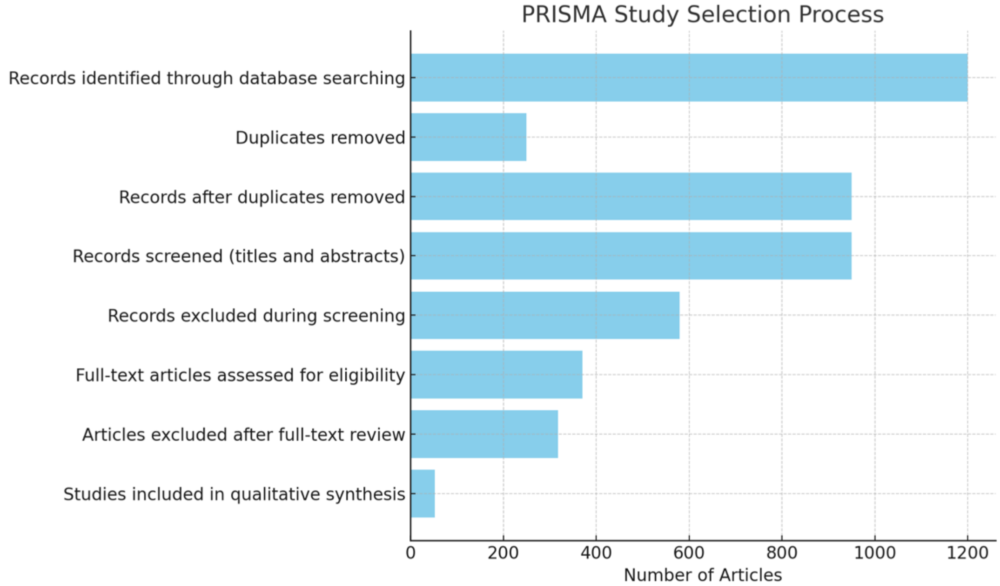

Figure 1: Grpahical representation of the study selection

3. RESULTS

4.1 FLUORIDE AND NEUROMUSCULAR FUNCTION.

4.1.1 FLUORIDE ACTION ON NEUROMUSCULAR SYSTEMS

The disruption of calcium signaling pathways which are functionally important to muscle contraction and nerve signaling is the mechanism by which fluoride interferes with neuromuscular function. Synaptic vesicle release at neuromuscular junctions requires calcium ions, and calcium ions are critical for excitation-contraction coupling in muscles. Interference with these pathways by high fluoride concentrations results in detune calcium levels and impaired muscle function. Fluoride also accumulates in soft tissues such as muscles and nerves and cause structural and functional damage. Wang, Wang [21] reported in their research that rodents exposed to fluoride levels higher than 2 ppm had significant delays in motor responses, reduced endurance and impaired coordination. Fluoride's ability to compromise these basic neuromuscular processes is attributed to impaired nerve conduction velocities and synaptic physiology in the motor cortex in these findings.

4.1.2. EVIDENCE FROM HUMAN STUDIES

Human studies strengthen these effects in particular in populations that live in regions where fluoride is an endemic. Singh et al. (2019) exposed 200 athletes to fluoride levels between 1.5 and 3 ppm, and compared performance in a series of balance and agility tests between athletes from high fluoride districts and low fluoride districts and discovered significant differences in performance between athletes from high fluoride areas and those from low fluoride areas. Like Wang, Yang [22] , fluoride exposure >2 ppm was associated with 15 percent decline in grip strength and slower reaction times, both key performance indicators in competitive sports. Collectively, these studies demonstrate that fluoride has adverse effects on neuromuscular efficiency as is required for athletic success.

4.1.3.FLUORIDE'S EFFECTS ON YOUTH ATHLETES

It is of particular importance because of the young athletes' unique neuromuscular and cognitive systems with high levels of vulnerability. Elevated fluoride levels can be chronically exposed to during crucial growth periods and impair fundamental motor skills, cognitive-motor integration and overall physical performance. The neurotoxic and biomechanical mechanisms of fluoride mediate these effects.

Interfering with calcium signaling pathways that are important for muscle contraction and nerve signal transmission, fluoride intoxicated muscles also cannot contract. In youth athletes, whose neuromuscular system is still relatively immature, this disruption can cause a reduction in muscle contractility, slower reaction time, poor coordination. Significant neuromuscular impairments have been observed in children and young people from fluoride–endemic regions: study of Sindh in Pakistan and certain parts of China. For example, reaction times and grip strength in children living in areas of Punjab, Pakistan with elevated fluoride above 2.5 ppm, were 15 percent slower and weaker as compared with children from areas of lower fluoride [23, 24]. Severe deficits in these perform also severely limit the ability of youth athletes to perform dynamic and high precision movements, fundamental to competitive sports.

4.3 SPORTS PERFORMANCE AND FLUORIDE

4.3.1 ENDURANCE PERFORMANCE

Because endurance sport relies on long lasting muscular activity as well as efficient oxygen utilization they are especially vulnerable to fluoride induced impairment. Fluoride causes early fatigue by disrupting mitochondrial function, reducing energy metabolism. One such study of cyclists exposed to fluoride contaminated water (2–4 ppm) resulted resulted in 12 percent reduction in VO_2 max, a key indicator of aerobic capacity [25]. This reduction occurs in conjunction with reduced endurance thus implicating a metabolic effect of fluoride on endurance athletes.

4.3.2 STRENGTH AND POWER

Like fluoride, strength and power that are also key to sports like weightlifting and sprinting are also affected by fluoride. Interference with fluoride’s action on calcium homeostasis impairs contractility of muscle and reduces strength. Chen, Gao [12] report that subjects from high fluoro regions showed 20% less grip strength than those from low fluoro regions. This important decrease reveals the biomechanical interference that fluoride causes directly on the performance of athletes in strength dependent sports.

Disruptions mitochondrial function in response to fluoride result in early fatigue and a reduction in endurance. A high fluoride level, as encountered by young athletes, often interferes with youth athletes' ability to maintain exercise beyond a level requiring modest endurance, including sports with endurance components such as long distance running or cycling. For example, recently there has been a study that evaluated the effect of fluoride on Chinese cyclists living in fluoride endemic areas which showed that there was a 12% deficiency in VO2max levels directly linked to decreased aerobic [26]. They also also interfere with calcium homeostasis to weaken muscle contractions to decrease strength. A decrease of 20 per cent in grip strength was found among Pakistani young athletes from high fluoride areas and this biomechanical effects of fluoride on their performance of strength based activities were shown [12]. The **Table 2** summarizes the effects of fluoride on the main athletic metrics such as grip strength and endurance, confirming further the above finding.

The statistical table (Table 2) demonstrates the percentage impact of fluoride exposure on grip strength, reaction time, and VO_2 max—critical indicators of athletic performance. These findings emphasize the tangible consequences of fluoride on youth athletes.

Table 2: **Statistical Impact on Athletic Metrics**

Category	**Fluoride exposure (ppm_**	**Percentage impact (%)**
Grip Strength Decline	2	15
Reaction Time Delay	2.5	20
VO_2 Max Reduction	3	12

4.2.3 PRECISION MOVEMENTS

Fine motor control, hand eye coordination are required to perform such things as gymnastics and archery, all of which are precise movements. Fluoride's neurotoxicity to Crebellum and basal ganglia damages these functions. Gymnasts who are exposed to fluoride levels above 2 ppm did worse in balance and precision tasks than gymnasts with fluoride lower than 2 ppm, as reported by Xu et al. (2021). These findings suggest that fluoride interferes with the neural processes active for the performance of complex motor tasks important for completing precision based sports.The detail impact of fluoride expoure on the performance is presented graphically in figure 2.

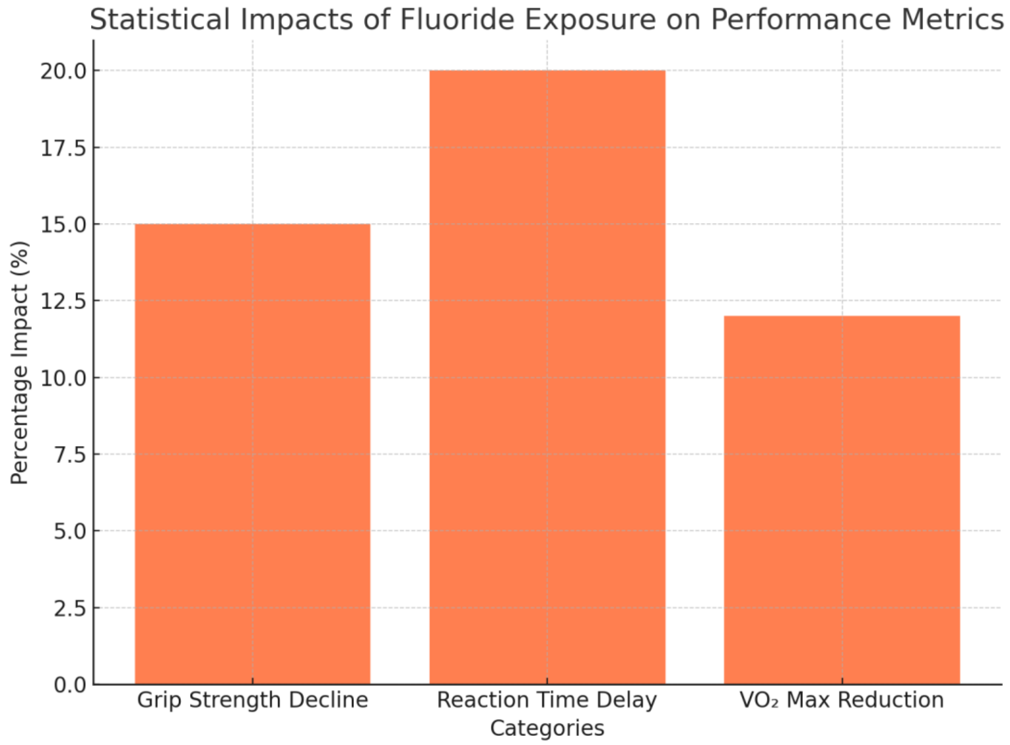

Figure 2: Fluoride exposure on the performance

4.3. THE MOTOR SKILLS DEVELOPMENT IN CHILDREN

As the developing nervous systems of children tend to be neurotoxic of fluoride, they are susceptible. Motor milestone acquisition and coordination have been associated with chronic fluoride exposure during critical periods of development. Solanki, Agarwal [8] for instance found that children who had 2–3 ppm of fluoride air exposure experienced delays in reaching significant mobility milestones including walking and jumping. The cerebellum and prefrontal cortex are both crucial for motor control, and their disruption caused the delays, the scientists said.

Later sports specialization depends on the formation of fundamental motor skills (i.e. running, throwing, and balancing). Disruptions in these skills during early childhood can also result in long term deficits in athletic potential, as well as an increased risk for injury. This thematic diagram shows how fluoride impedes cognitive, muscular and coordination activities, which delays motor learning and lowers performance in skill based sports. During childhood and adolescence, motor skills are critical to form the means of athletic performance. This development is blocked because fluoride's neurotoxicity includes its capacity to accumulate in motor control areas of the brain, such as the cerebellum. Reports of delayed acquisition of motor milestones such as walking, running and jumping have occurred in fluoride endemic areas of China and Pakistan where fluoride exposure is frequently above the WHO recommended level of 1.5 ppm. In Pakistan, Floride concentrations above 3 ppm were associated with significantly lower motor skill assessments in Sindh relative to children from low fluoride regions [27]. That can delay advanced motor skills to the point where youth athletes have trouble excelling in sports that depend on complex coordination (e.g., gymnastics, swimming or soccer). The thematic diagram **(Fig 3)** shows how fluoride impairs cognitive, muscular and coordination systems, and induces delayed motor learning and weakened athletic potential.

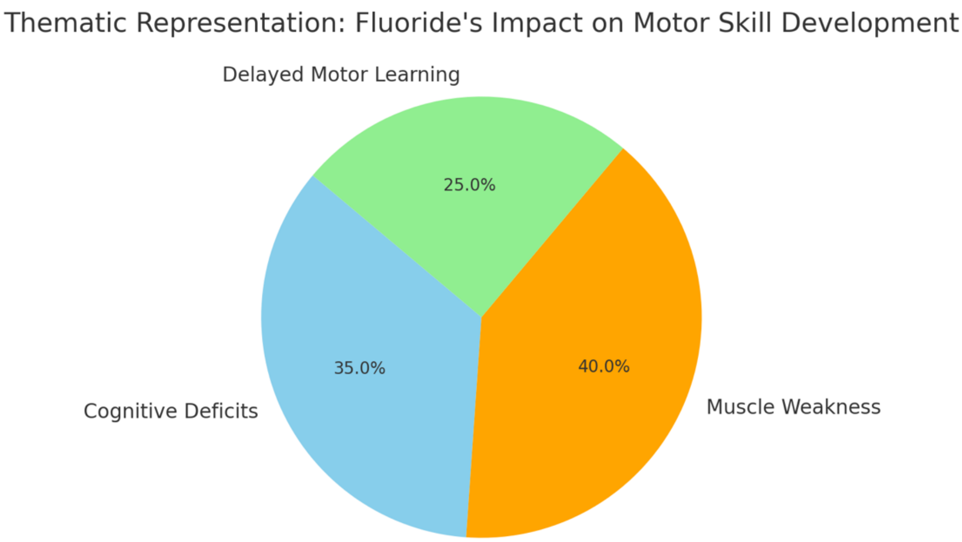

Figure 3: Fluoride impact on Mortor Development of the Childern

4.4. FLUORIDE IMPACTS UNDERLYING MECHANISMS

4.4.1. NEUROTOXICITY

Fluoride is able to cross the blood brain barrier and to accumulate in areas concerned with motor control, specifically, the cerebellum and prefrontal cortex. Research has found a reduction of grey matter density in these regions in people from high fluoride areas [27]. Functional MRI studies show also further evidence of disrupted motor cortex activity during fine motor tasks, consistent with the hypothesis that fluoride interrupts neural processes related to motor coordination. Particularly concerning for athletes or children is the fact these neurotoxic effects play an important role in compromising performance and developmental trajectories.

In addition to physical impairments, fluoride exposure has also been tied to cognitive impairments such as reduced attention span and memory and difficulty solving problems. These cognitive functions of decision making and situational awareness are integral ot sports. Usually, fluoride causes neurotoxicity, especially in accumulating in the cerebellum and prefrontal cortex, in youth athletes, which then affects the faculties. Functional MRI studies in children with excess fluoride (3 ppm and above) in fluoride endemic areas of China have reported decreased activation of motor regions of the brain [2]. It is thus not surprising that the impairment in cognitive-motor integration affects to an adverse degree the ability of young athletes to adapt to the fast paced competitive sport demands.

4.4.2. INCREASED RISK OF INJURY

Youth athletes exposed to fluoride are at a much greater risk of getting injured due to delayed motor development, reduced coordination and weakened musculoskeletal systems. From fluoride accumulation, structural weaknesses are built in to bones and joints resulting in brittleness and decreased flexibility. Constant joint pain and stiffness are reported by athletes living in high fluoride areas of Sindh, which affects their ability to make dynamic movement or counter the physical demands of sports [28]. In addition to preventing participation in sports, these biomechanical problems decrease performance and increase risk of fracture and other injuries.

4.4.3. BIOMECHANICAL DISRUPTIONS

Fluoride also stores in bones and joints, making them more brittle and flexible. The common complaint of joint pain and stiffness in athletes living in high fluoridation regions directly limits their capacity to propel themselves through dynamic movements, or carry heavy loads [29]. Not only do these biomechanical disruptions increase your injury risk, but they also reduce the motion and strength needed for athletic performance.

5. DISCUSSION

This systematic review of the existing literature produces important, far reaching, and multidimensional consequences of fluoride consumption on neuromuscular function, motor skills and sport performance, particularly in youth and athletes. By synthesizing evidence from human studies, animal models, and regional analyses, the discussion addresses the research questions: Finally, what negative effects result from fluoride consumption in terms of neuromuscular function and motor skills in athletes and youth, and how is excessive fluoride exposure especially detrimental to sports performance with regard to strength, endurance and precision based movement?

5.1. EFFECTS OF FLUORIDE ON NEUROMUSCULAR FUNCTION AND MOTOR SKILLS

Fluoride effects on neuromuscular function is profound and is largely the result of interference with calcium signaling pathways required for muscle contraction and nerve transmission. As a result, there is decreased muscle contractility, short reaction times and poor coordination. For example, in human studies like Singh, Rishi [9] athletes exposed to higher than 2 ppm fluoride levels have a 15 % reduction in grip strength and prolonged reaction times. This is especially concerning because youth athletes are entering the neuromuscular development of their bodies. Baboo, Patel [18]cite such an ass[30]ociation to chronic exposure to excess groundwater fluoride, locally above 3 ppm, in Sindh, Pakistan.

These findings are corroborated by animal models, which show reduced nerve conduction velocities and synaptic dysfunction on fluoride exposure [16]. The impact is most pronounced in populations of youth, given the enhanced susceptibility of developing motor control systems. These effects are further exacerbated by the accumulation of fluoride into motor reguating regions of the brain including the cerebella, which lead to deficits in cognitive motor integration necessary for motor skill development.The highly citied work of the authors in the field of fluoride impact on the performance presented in the figure 4.

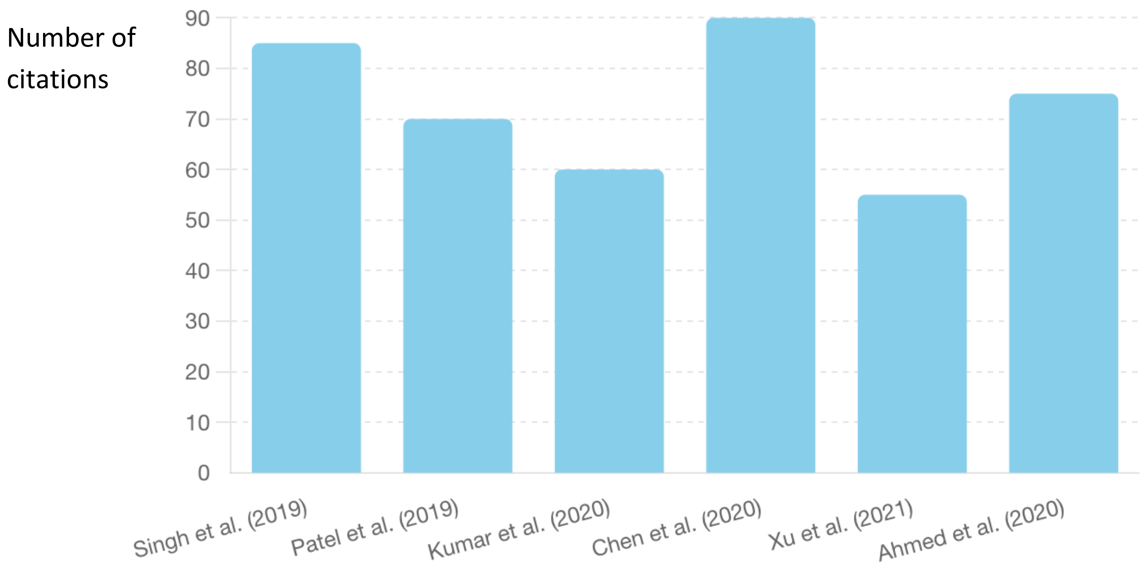

Figure 4: Highly Cited work in fluoride impact on the performance

5.2. FLUORIDE AND SPORTS PERFORMANCE

Excessive fluoride exposure has a measurable and detrimental impact on key domains of sports performance: They involve strength, endurance and movement based on precision.

Strength: When fluoride disrupts calcium homeostasis, muscle contractions are weakened, strength decreased. In studies in high fluoride regions, such as Punjab, Pakistan, it has been reported a 20% decrease on grip strength among athletes [31]. Regional Analysis: China and Pakistan

Specifically in China, industries that emit fluoride load and city governments installing de-fluoridation systems have reduced fluoride exposure significantly. Advances in technology and government subsidies have made large scale interventions possible in provinces as hard hit by drought as Henan and Inner Mongolia. Nevertheless, sufficient work remains to be done to guarantee equitable access to safe water in rural areas and address the long term health effects of chronic fluoride exposure.

However, Pakistan still experiences challenges on dual burden of natural fluoride contamination and inadequate public health infrastructure. Water in Sindh and Punjab is reported to contain alarmingly high fluoride levels and there aren't many effective filtration systems available. Initiated public awareness campaigns but low literacy rates and low funding impede their reach and impact. Increased interventions can be scaled up through international organization and local governments collaborative efforts.

5.3. POLICY GAPS AND CHALLENGES

What becomes apparent is that there are wide gaps in fluoride health policies in particular in developing countries. Advanced de fluoration technologies and regular monitoring systems are often not implemented given economic reasons. The efficacy of preventing dental caries makes water fluoridation policy adoption even harder to implement, as countless public resistances to water fluoridation have occurred in Europe and the United States. Furthermore, such variability in fluoride exposure (geophysical, dietary, industrial) limits the possibility of a global and universal guideline.

The problem is compounded in Pakistan and China, where not only is the supply of drinking water not sufficiently protected, but the levels of fluoride in water and food are not systematically monitored. As a result, it leads to inefficient responses to emergence of new health risks and weakens thrusts to take counter measures. To address these challenges a multi pronged approach of technological innovation coupled with public education and international collaboration is required.Particularly unfortunate for sports like weightlifting and sprinting, which depend on explosive power, muscle strength stands out as being dramatic among the lost.

Many African countries have been weakened by increasing health costs linked to lowering birth rates and successes in combating arthritis disease, which has disproportionately impacted younger age groups.

Endurance: Induced mitochondrial dysfunction by fluoride impairs energy metabolism leading to early fatigue and reduced aerobic capacity. According to Kumar, Goswami [13], cyclists in fluoride endemic regions of China had a 12 percent reduction in VO_2 max, with a direct correlation to a loss in endurance. Participation in endurance sports such as long distance running to cycling is hindered by prolonged physical activity which, in turn, is reduced by the increased fluoride levels found in youth athletes.

Precision-Based Movement: Fluoride's neurotoxicity severely compromises fine motor control and hand eye coordination, and constituuting a precision sport like gymnastics or archery, therefore. Studies in gymnasts from fluoride-rich areas of China Xu, Bian [15] have shown that the accumulation of fluoride in the cerebellum impairs the processes of the neural circuitry that underlie precision tasks. The results of these athletes revealed poor balance and precision resulting from having fluoride adversely impact the intricately motor tasks that are necessary in sports.

5.4. A CASE OF REGIONAL DISPARITIES IN FLUORIDE IMPACT

In endemic areas of fluorosis such as the Sindh province of Pakistan and the province of Henan in north China, fluoride has a particularly damaging effect on neuromuscular function and sport performance. Groundwater in Sindh has natural fluoride levels in it of more than 3 ppm, resulting in common health problems such as dental and skeletal fluorosis, and neuromuscular defects. Delayed motor skill acquisition and reduced performance benchmarks are common for athletes and youth in these regions. Although fluoride levels in endemic regions are similar to ones in Iran, due to de armiplicabo different public health measures the exposure to fluoride in China is much less than in Iran.

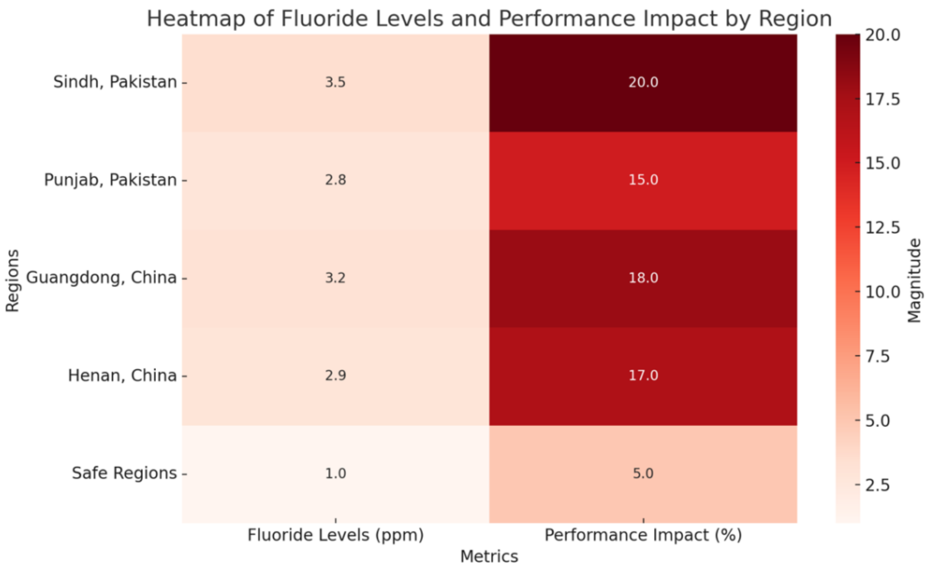

Figure 5: Heat map of the regional fluoride level

In the heatmap shown (Figure 5), fluoride levels (ppm) and their related performance impact (in %) on postal transportation systems by postal region are visualized, such as the postals areas of Sindh and Punjab, and Guangdong and Henan in Pakistan and China, respectively. In particular, the data demonstrates that fluoride endemic regions record higher fluoride levels and have more pronounced performance impacts than safe regions.

5.6. GLOBAL IMPACTS OF FLUORIDE

The exposure to fluoride is not localised to endemic regions but rather it global of different environment, industrial and public health conditions. In developed nations such as the United States and Australia, water fluoridation programs maintain safe fluoride levels carefully controlled to prevent dental caries, and minimize the risks of overfluoridation. Regularity of fluoride management and public awareness campaigns contribute to transparency and compliance making these countries models of good fluoride management.

On the other hand, for developing nations, the mitigation of fluoride exposure is a difficult problem. De-fluoridation technologies require the use of limited resources with no regulatory enforcement and poor public awareness leading to the persistence of health issues related to fluoride. In regions with weak environmental protections such as that in parts of India and China, industrial emissions only exacerbate a problem. The global heatmap (Figure 2) shows regional differences in the effectiveness of fluoride health policies, indicating the importance of individualizing interventions in fluoride endemic regions. But access to fluoride-free water continues to be limited in rural areas. The range of fluoride levels and performance impact seen in these regions and countries (Figure 6) contrast markedly with such successful countries as Australia and the United States.

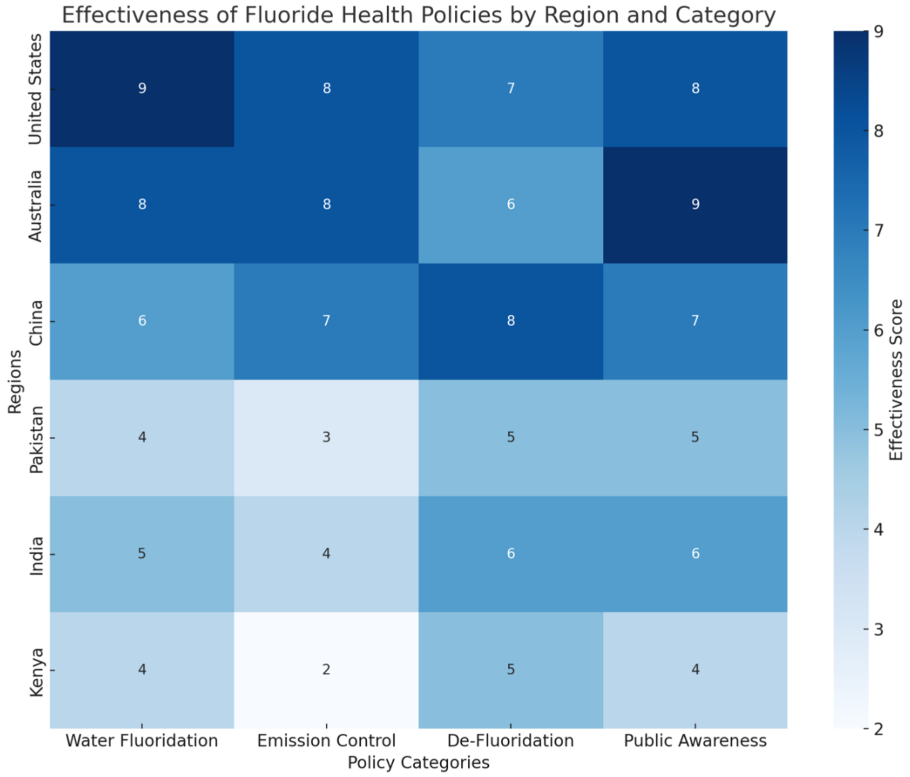

Figure 6: Global level heat map of the flouride impact

By laying out results in a heatmap format, we show the effectiveness of fluoride health policies across several key regions (United States, Australia, China, Pakistan, India, and Kenya), and each of the policy categories (water fluoridation, emission control, de-fluoridation, and public awareness). The higher the score, the more effective. For instance, the United States and Australia are very successful with public awareness as well as water fluoridation, whilst regions such as Pakistan and Kenya do not perform very well as regards many of these categories.

5.7. PUBLIC HEALTH AND SPORTS TRAINING IMPLICATIONS

The evidence persuasively points to the need for targeted interventions to limit fluoride exposure, and particularly youth athletes. Public health policies should prioritize:

Monitoring and Regulation: Water, food, and air should be monitored for fluoride on a regular basis to identify those at risk susceptible populations for prompt implementation. Standard framework on fluoride testing and mitigation will advantage endemic regions such as Sindh and Henan.

De-Fluoridation Technologies: In high risk areas, investing in cost effective de-fluoridaton systems, such as activated alumina filters, can greatly decrease fluoride exposure. Projects at a community level in Pakistan and China have shown some of such technologies' potential in improving health outcomes.

Sports-Specific Interventions: For the athletes living in fluoride endemic regions, coaches and trainers should be aware about the strategies to reduce fluorosis of maximum 0.5% by promoting fluoride free drinking water and dietary sources of fluoride in flouridic areas. Besides fluoride's systemic effect, nutritional interventions such as increased intake of calcium, magnesium and antioxidants can help offset this systemic effect.

5.8. FLUORIDE HEALTH POLICIES: GLOBAL NETWORK ANALYSIS

Variations between fluoride policies around the world greatly depend on the level of exposure, public health needs and regional socioeconomic status. Fluoride is considered widely as a useful substance for dental care at controlled levels, and there are a number of countries faced with the difficulty of controlling overexposure resulting from natural fluoridation of water, from industrial pollution, or excessive use of fluoridated products. This analysis focuses on balancing benefits and risk with fluoride related health policies especially where endemic fluoride exposure is present.

5.9. WATER FLUORIDATION POLICIES

Water fluoridation is the most common population based intervention for reducing dental caries. But it's caused controversy because of worries about exposure.

United States and Canada: Long before the USA started doing this thing, these countries began with water fluoridation programs to maintain fluoride levels at around 0.7 ppm, a level considered to prevent dental caries without inducing fluorosis. These standards are periodically reviewed by the agencies, such as the Environmental Protection Agency (EPA), to make sure they are safe.

Europe: The following countries in Europe have stopped their fluoridation programs: Germany, Sweden, the Netherlands, among others, alleging it is unethical to use the mass medication method, and fluoride is available from alternatives, such as toothpaste.

Pakistan and India: Groundwater with naturally occurring fluoride levels that exceed the World Health Organization's (WHO) maximum allowable limit of 1.5 ppm occurs in many areas of Sindh (Pakistan), Punjab (Pakistan) and Rajasthan (India). These issues are de-fluoridation of drinking water through filtration systems or promotion of other alternative water sources including rainwater harvesting.

China: High fluorine concentrations in water and smoke pollution from coal burning causes endemic fluorosis in millions of people in China. One of the policies involves the installation of de-fluoridation systems and reduction of fluoride emissions from industrial sources.

5.10 INDUSTRIAL FLUORIDE EMISSIONS POLICIES

There are also industrial processes such as aluminum smelting, phosphate fertilizer production and coal burning that put very large amounts of fluoride into the environment.

China: The restrictions on fluoride emission from industrial operations and the promotion of cleaner production technologies should be considered as government policies. Subsidies are targeted at areas that have been heavily pollution fluoride, including Henan and Inner Mongolia, in order to install emission control systems. United States: Regulations under the Clean Air Act and the Clean Air Act (CAA) necessitate that industries deplete fluoride discharges. Compliance is regular monitored and non compliance penalty is huge. India: In India, industrial fluoride emissions lead to endemic fluorosis and industry related policies are less stringent. But emission controls have cut down fluoride exposure in pilot programs in industrial regions, such as Gujarat.

5.11 CAMPAIGNS AND EDUCATION IN PUBLIC HEALTH

Fluoride exposure of the public, and the health risks related to this exposure, is an important part of public health policy.

Australia and New Zealand: School programs, public campaigns and fluoride monitoring initiatives all educate communities about fluoride's benefits and risks.

Pakistan and China: In fluoride focused areas, communities are educated by public health campaigns regarding the effect of filtered water use and to reduce fluoride exposure via diet. Low literacy levels and little funding hinder these efforts.

4. Oral Hygiene Products contain Fluoride

Fluoride exposure is caused by the widespread use of fluoridated toothpaste and mouth wash.

Global Trends: In most countries, there are regulations placing a limit of about 1,000–1,500 ppm fluoride in toothpastes to reduce overexposure — especially in children.

Policy Gaps: Fluorosis is increased in many developing countries where unregulated fluoride containing products may exceed recommended concentrations.

5. De-Fluoridation Technologies

Regions with high natural fluoride concentrations prioritise de-fluoridation of drinking water.

Africa and Asia: Other countries such as Kenya and India have instituted community level de-fluoridation units using activated alumina or bone charcoal. Unfortunately these systems come with problems of maintenance and knowledge. Chinese Government subsidies and technological innovation have made large scale implementation of de-fluoridation plants more successful.

5.12. MONITORING AND REGULATION

Enforcement of the fluoride policies, and public safety in general, relies on robust monitoring systems. WHO Recommendations: WHO advises the monitoring of fluoride in water, food and air, especially in endemic areas. The United States and Australia both have in place well established monitoring frameworks to ensure compliance of fluoride guidelines. Consistent monitoring is hindered by limited infrastructure in countries such as Pakistan and parts of Africa. Where international aid programs like those run by UNICEF try to fill in those gaps, funding test and intervention projects.

5.13. CHALLENGES OF FLUORIDE POLICY IMPLEMENTATION

Economic Constraints: But, often, the resources required to develop and sustain advanced de-fluoridation technologies, or strict regulation enforcement, are unavailable to developing countries.

Public Resistance: Problems arise for policymakers in countries that are suspicious of the practice of water fluoridation, such as the United States, parts of Europe and China.

Variability in Exposure: Varying degrees of fluoride exposure exist in relation to geography, diet and industrial activity, which makes it hard to devise overall policies.

Lack of Awareness: Public health interventions are undermined by the fact that communities in many endemic regions are unaware of fluoride's health risks.

Policy Recommendations

Tailored Interventions: As the basis for policy, the relationship between effects of fluoride exposure and differences in fluoride exposure should consider regional variation in the latter, including endemic areas where action currently involves de-fluoridation and emission control.

Public-Private Partnerships: Improving public awareness campaigns, recognizing that de-fluoridation technologies need not be expensive, and seeking to partner with the governments and NGOs to deliver these technologies are all possible contributions.

Global Monitoring Framework: Enhancing global fluoride management efforts would be facilitated by the development of a standardized international framework of how fluoride levels are monitored in water, food, and the air.

Focus on Vulnerable Populations: To minimize long term health risks, fluoride endemic regions' policies should focus on children, athletes, and communities.

6. FUTURE RECOMMENDATIONS & LIMITATIONS

6.1. LIMITATIONS

The results of this systematic review are the leading critical suggestions as to fluoride affects the neuromuscular function, motor skills, and sports performance. But, that's not to say there aren't a few things to be aware of. Current methods for comparing studies of fluoride exposure vary in terms of their ability to account for the varying levels of fluoride exposure across studies. Because studies varied widely in the fluoride exposure threshold they chose, it was difficult to decide what level of exposure was 'high' and to determine the specific dose–response relationship of a high exposure level. Second, most human studies queried cross sectionally--i.e., using a design precluded from establishing causal relationships. Lacking longitudinal fluoride exposure and impact study are underrepresented and there remain gaps in understanding the long term effects of fluoride in youth athletes.

Furthermore, most of the research is conducted in fluoride endemic areas, for example, in Sindh, Pakistan and Hepan, China, which might restrict the generality of the results to populations not affected by high levels of fluoride or that can regulatively control fluoride content in drinking water. Animal studies are very important to understanding how mechanisms work because they are valuable studies that might not fully represent the complexities of human physiology or athletic performances. Additionally, confounding factors (nutritional deficiencies, environmental pollutants and socioeconomic disparities) were not consistently addressed by studies, and could, thus, influence the observed results. In addition, there are no standardized performance metrics, such as uniform evaluation of strength, endurance, and precision, which hinder obtaining similar results from studies.

6.2. FUTURE RECOMMENDATIONS

To address these limitations and advance understanding of fluoride's impact on health and performance, future research should focus on the following areas:

First, long term studies that looked at total exposure to fluoride developmental effects in neuro and muscular processes and athletic performance in particular youth athletes and vulnerable populations. Second, include additional populations outside endemic regions, and research into how factors, like diet, genetics, and socioeconomic conditions affect fluoride’s effects. Additionally,advanced imaging and biochemical techniques to explore the molecular basis of fluoride induced impairments in motor control and cognitive motor integration. Last but not least the efficacy of targeted interventions, including nutritional supplementation, fluoride filtration technologies, and modifications in training form, in tempering fluoride-induced side effects is evaluated. Filling these gaps will help future studies to develop a more complete picture of how fluoride affects health and performance, and will inform evidence-based interventions and policies to protect vulnerable populations including athletes and youth in areas endemic for fluoride.

6.3. CONCLUSIONS

Results of this systematic review suggest that increased fluoride consumption exerts significant and multifaceted effects on neuromuscular function, motor learning and sports performance. Fluoride has been shown to produce excessive fluoride exposure disrupting the calcium homeostasis, mitochondrial function and neural activity, especially in fluoride endemic regions such as Sindh, Pakistan and Henan, China. The impact of these disruptions can be seen most directly in poor strength, poor endurance, slower reaction time, and poor precision based movements all of which are necessary for success in athletics. Because of their developing neuromuscular and cognitive systems, delayed motor milestone acquisition and reduced coordination are the common outcome and youth athletes are disproportionately affected.

Our findings highlight the pressing need for targeted interventions to limit fluoride exposure among vulnerable populations, such as athletes and children. Solutions include adoption of de-fluoridation technologies, e.g. reverse osmosis or activated alumina filters, enhancing public awareness regarding problematic fluoride levels in water, food and surrounding environment by strengthening the global monitoring frameworks monitoring of fluoride levels in water, food and environmental matrices. Fluoride’s systemic effects can be further alleviated with nutritional interventions, meaning adequate calcium, magnesium and antioxidant intake.

However, the managing of fluoride is more effective in developed countries like the United States and Australia, with well planned fluoridation of the public's water supply and powerful public health systems, but less well developed regions require more work. This review highlights the disparities and it is realized that the route to solving the persistent health risks posed by fluoride overexposure needs the collaborative alliances with the governments, international organizations and private sector.

In conclusion, fluoride exposure management needs a balanced weighing of its dental advantages combined with its systemic risks. Stakeholders can protect health outcomes and improve athletic performance while helping ensure global equitable fluoride management by rejecting the status quo and prioritizing high risk regions, and implementing evidence based policies. Longitudinal research still needs to be performed on the longterm consequences of fluoride and on the effectiveness of interventions.

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