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Article

Bidirectional promotion of adolescent physiological mechanisms and mental health: An analysis based on human biomechanical data

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Abstract: The focus of the study is on the interrelation between hormonal secretion, cellular activity and skeletal growth with physiological advancement and depression in adolescents. To conduct a more in-depth analysis, it employed a longitudinal research strategy and recruited 436 adolescents who measured between the ages of 12 to 18 along with an 8–10 years Hispanic male. Over the course of 24 months, multiple sets of data were gathered, which included insulin-like growth factor-1 (IGF-1), cellular metabolism markers, GH, bone mineral density (BMD) and psychological indicators. The data gathered showcased multiple correlations between endocrine parameters and GH levels which were linked with depression $r = 0.76$, $p < 0.001$ and emotional regulation $r = 0.82$, $p < 0.001$. The clinical implications highlight the better understanding of the biomechanical-psychological interaction in development of adolescents and how to tackle such an issue with evidence-based intervention.

Keywords: adolescent development; growth hormone (GH); depression; bone mineral density (BMD)

1. Introduction

The developmental phase of adolescent maturity is essential, as the individual undergoes notable physical and psychological changes, thus presenting new sets of opportunities and complexities in the course of human development [1]. The evolution in the technology of the biomechanical analysis has dramatically improved our chances to assess the multifaceted relationship between different biological systems and mental health during adolescence [2,3].

Aspects of the relationship between patterns of hormonal regulation and developmental psychology during the adolescent stage have emerged to be a pressing issue. It was discovered that fluctuations in growth hormone secretion and cortisol rhythmic fluctuations have a significant impact on emotional self-regulation and cognitive processing [4,5]. These hormonal modifications also carry significance for the inner emotional or psychological resources for supporting physical development during adolescent years and in the development of psychological stability and emotional strength [6].

The increasing interest in cellular metabolic activity in factors related to adolescent years, among others, has established the link between mitochondrial activity and mental health factors [7]. The adolescent stage of maturity is a dynamic period wherein trends in cellular energy usage during development have also been found to associate highly with cognitive functioning and the capacity to self-regulate emotions [8]. Finally, oxidative stress markers are being highlighted as possible proxies for physiological and psychological health in adolescents [9].

The increase in virtually all body parts during adolescence, as well as the increase in bone mass, is a fairly complex process that assists in describing the biological-psychological dimension. Recent studies have uncovered substantial links between bone mineral density, growth rate, and a number of mental health components [10,11]. How the skeletal system affects the development of the brain and the stability of its emotional component is conveyed by the new concept of the bone-brain axis [12].

Quite intricate processes such as neural-endocrine interactions during the teenage period have been recently and increasingly well defined, exploring rather the two-way effects of hormonal systems and neural growth [13]. The combination of these advanced imaging technologies with hormonal studies has exposed some new possibilities for the fulfilment of the endocrine function in response to a previously determined pattern of brain development [14,15].

Integrating these complex relationships encompasses an understanding that is necessary for effective interventions that target both the physiology and psyche of adolescent development. Adopting such a thorough approach to considering adolescent health entails a new way of attributing and addressing developmental hurdles during this extremely important phase.

2. Literature review

2.1. Current understanding of biomechanical parameters

2.1.1. Hormonal secretion

Current studies have improved our understanding of adolescent hormone secretion patterns and how they influence physiological and psychosocial development. Growth hormone (GH) secretion has a distinct pulsatile pattern throughout adolescence with the peak amplitude occurring during slow-wave sleep [16]. These GH patterns aid physiological growth and cognitive development as some studies show that there is a strong correlation between the levels of GH and emotional control abilities [17].

Thyroid hormone regulation during adolescence shows interactions with other endocrine systems whereby metabolic rate and neural development are adversely affected. There is conclusive evidence that slight variations in the levels of the thyroid hormone affect the stability of moods and even cognition during this period of development [18]. Adolescents' cortisol rhythms exhibit specific profiles while recent investigations reveal that changes in daily cortisol rhythms are closely related to mental stress and adverse emotions [19].

The development of sex hormones during the adolescent stage is one of the other hormones secreted by the body that has a strong inverse relationship with well-being; its inverse relationships include testosterone and estradiol levels in physical maturation. Longitudinal studies that were conducted recently have indicated that the sequence timing of the development of sex hormones can influence social-emotional growth and changes as well as the mental health of an individual [20].

2.1.2. Cellular activity

The biological processes that occur at the cellular level can be observed during the period of puberty and they seem to have an impact on the physical changes and the psychological processes of an individual. Recent findings show that mitochondria within adolescent cells fluctuate in energy demand depending on the stage of development they are currently within the network [21]. There is a strong correlation between energy substance metabolism and psychological well-being as such variations in metabolism rates were correlated with cognitive tasks and emotional regulation abilities.

Recent studies have also found that mitochondrial function plays a vital role in adolescent development as structural neural alterations and cognitive growth were found to be influenced by mitochondrial efficiency [22]. Causative research gives us insight into the dynamic nature that cellular energy use takes on during the stage of adolescence, as for parameters of physical growth and psychological growth, ATP production and consumption rates were shown to have a strong correlation with them [23]. Understanding oxidative stress markers has proved to be valuable for the assessment of cellular health in the adolescent phase as it was found out during this stage that increased levels of oxidative stress could be a possible reason for both psychological and physical susceptibility [24]. Also, the interactions between pro-oxidants and cellular antioxidants were found to play an important role in the adolescent stage as strong cellular resilience and the ability to adapt on a psychological level was recorded [25].

2.1.3. Skeletal growth

The bone development during mid-adolescence is a time when many new biological processes occur simultaneously. It has been shown that bone mineral density accrued during these years is important with respect to physical growth, but there is evidence suggesting that it is also related to some unexpected blunt factors, including psychological health [26]. Advanced imaging techniques exist and have demonstrated that bone mineral density is acquired in a certain manner and has an effect on prolonged bone health and may alter the development of the brain through bone factors [27].

Interesting patterns of hormones have been described in relation to growth plate activity, with increased growth during this stage of development being associated with lift/hormonal signaling pathways [28]. In recent studies, coupled with other instrumental analyses, skeletal growth, its pace has been the most escalated as a determining parameter of developmental change in the context of new integration. Physiological as well as psychological adjustment during the adolescent phase can be impacted by changes in the skeletal maturity rate [29]. Studies conducted on skeletal mineralization and hormonal factors such as bone turnover suggested for a lifetime that activities of the brain, particularly due to the activities of bone [30]. This type of crosslink makes it crucial to have regular follow-ups on physiological skeletal differentiation to determine the health of adolescents.

3. Methodology

3.1. Research design

This investigation adopted a multi-factorial longitudinal design approach that lasts 24 months to evaluate the interrelationships that exist between biomechanical elements and the psychological growth of adolescents. The approach is time-sensitive as it focuses on the changes that occur and the developmental trajectories of multiple physiological systems and psychological domains.

The sample consisted of 436 adolescents aged between 12 and 18 years at the baseline (228 females, 208 males) who were of different socioeconomic and ethnic backgrounds in certain urban and suburban areas. The participants in this study were evaluated after a period of time, and the data collection frequency was adjusted per the specific resource category. Hormone determinations were executed monthly as those parameters are rather unstable, whereas cell activity metrics were performed every 3 months, and various parameters assessing skeletal growth were done every six months.

The advanced imaging, biochemical and structural psychological exam that all the participants underwent was the varied assessment method for the research. A thorough follow-up plan was established to ensure retention so as to reduce attrition biases. Apart from that, multiple environmental and lifestyle variables were manually controlled and later adjusted using statistical techniques.

Quality assurance strategies ensured qualified data collection, regular checks on measurement devices, and continuous updating and training of research staff. The same study framework had strict inbuilt validation to maintain measurement invariance across time and place. In a parallel control group design, 150 age-matched subjects also underwent the same tests to evaluate normal age-related growth and seasonal changes.

The study's design allowed for examining both direct and indirect effects of physiological variables on psychological measures while controlling for individual differences and developmental patterns. Having such a long study period made it possible to track both short-term fluctuations and longer-term trends associated with the adolescent developmental process.

Biomechanical measurements

Table 1. Biomechanical parameter measurement framework.

Parameter Category	Specific Measurements	Frequency	Analytical Method
Hormonal Secretion	Growth Hormone (GH)	Monthly	ELISA
	Thyroid Hormones	Monthly	RIA
	Cortisol	Monthly	LC-MS/MS
Cellular Activity	Metabolic Rate	Quarterly	Respirometry
	Mitochondrial Function	Quarterly	Flow Cytometry
	Oxidative Stress	Quarterly	Spectrophotometry
Skeletal Growth	BMD	Bi-annually	DXA Scan
	Growth Plate Activity	Bi-annually	MRI
	Bone Markers	Quarterly	ELISA

Using the most technologically advanced instruments, the biomechanical parameters were evaluated and then it was ensured that the data collected was reliable and valid. The measurement framework included a comprehensive assessment of such hormonal secretion dynamics, cellular activity dynamics and skeletal growth indicators. Laboratory procedures were followed so that all the measurements were taken in a controlled environment while the standardized operating procedures were also followed. The data was generally structured into tables whereby specific objectives and their corresponding frequencies were presented in various tables under specific criteria as shown in **Table 1**.

3.2. Data collection methods

3.2.1. Hormonal analysis

In this research, the researchers employed a particular methodology to analyze the hormones which incorporated the use of blood sampling with 20-minute intervals to capture the fluctuations in the release of GH while also conducting a 24 h profiling for GH. The analyzing techniques employed in this approach were ultra-sensitive chemiluminescence, enabling the researchers to identify and encapsulate the amplitudes, frequency, and circadian variation patterns in the hormonal activities of the subjects.

This aspect of the research was further supplemented with the monitoring of the cortisol levels through saliva collection devices at five distinct intervals which include aggregation of these hormones, and in order to further guarantee the precision and the efficacy of the devices that the researchers possessed, they utilized liquid chromatography-tandem mass spectrometry (LC-MS/MS).

Furthermore, dismissing traditional methods, the blood hormone assays incorporated automated immunoassays which allowed the researchers to measure the thyroid hormones, sex steroids and regulatory peptides concurrently. To assess the IGF-1 levels, enzyme-linked immunosorbent assay (ELISA) was utilized. Maintaining the standard of accuracy and reproducibility, a two-fold analysis was performed while also conducting internal quality and external validation.

3.2.2. Cellular parameters

The study of cellular dynamics utilized advanced techniques to evaluate the aspects of cellular dynamics associating it with cellular function most effectively. Measurement of mitochondrial functions included the employment of high-resolution respirometry together with fluorescence assays to determine the capacity for oxidative phosphorylation, conduction of membrane potential and other electron transport activities in distinct peripheral blood mononuclear cells (PBMCs). These parameters were measured utilizing the Oroboros O2k device that provides the means for proliferation of mitochondrial respiratory states in real time.

The determination of metabolic rates was recorded for the organism and even cellular respiration. The research into indirect calorimetry was employed for the basal metabolic rate; on the other hand, the cellular metabolic profiling employed the use of Seahorse XF analyzer which in real time measured the oxygen consumption (OCR) and extracellular acidification (ECAR) rates. The oxidative stress assessment utilized a number of markers, including but not limited to measurement of 8-isoprostanes and protein carbonyls in tandem with 8-hydroxy-2-deoxyguanosine, which mostly relied on LC-MS.

Utilization of energy was measured and characterized through the use of nuclear magnetic resonance spectroscopy coupled with mass spectrometry where key intermediates of metabolism and or energy substrates were analyzed, more specifically this analysis included the evaluation of ATP/ADP ratios, lactate and glucose production rates in order to provide an insight and understanding on the cellular bioenergetics and metabolism across the different physiological conditions.

3.2.3. Skeletal measurements

Skeletal measurement was carried out using advanced imaging techniques alongside biochemical methods as an integrated approach. The subjects underwent bone scanning at different skeletal sites, including the lumbar spine, proximal femur and total body, using the Hologic Discovery A densitometer which is modified for dual-energy X-ray absorptiometry (DEXA) technology. Bone Mineral Density (BMD) from DEXA scans was estimated taking into account pediatric software protocols also considering age and sex matched Z-scores.

For skeletal imaging, multi-channel cartilage sensitive sequences were utilized along with high resolution MR to assess and evaluate the morphology and functionality of the growth plate. 3Tesla scans of T1 and T2 were performed to visualize the size, structure and composition of the growth plate. Validated image processing algorithms were employed and quantitative analysis of growth plate parameters varied by type and ratio were biased during the validation integration.

Markers of bone turnover were evaluated by sequential assessment of formation and resorption markers. Immunometric assays with automated quantifiers served to measure serum concentration of procollagen type I N-terminal propeptide (PINP) and C-terminal telopeptide (CTX) in the serum. The required anthropometric protocols were also followed including measuring height, sitting height, and length of the legs and arm span and the calibration of stadiometers with anthropometric devices. These measurements were conducted by trained anthropometrics with established inter-rater reliability, and the reliability values were assessed before each measurement to enhance precision and effectiveness.

4. Results

4.1. Hormonal parameters

Growth hormone patterns

The analysis showed a steady increase in the mean GH levels over the two-year study period along with its positive association with the mental health scores as shown in **Figure 1**. As per the progress report, mental health scores improved from 72.5 to 86.9, as the study progressed—a change aligned with the GH levels. Overall, GH levels were found to be in an approximate range of 2.3 ± 0.4 ng/mL and 4.2 ± 0.3 ng/mL during the first ES period of 0–6 months and the final ES period of 0–6 months respectively. The increase in the scores was linear, following closely to the linear trend with $r = 0.89$, $p < 0.001$.

The statistical analysis reflected significant changes in the secretion of GH across time periods (ANOVA, $F = 14.32$, $p < 0.001$), allowing for post hoc examinations to provide further insights on the contrasting modifications spanning various time intervals. The greatest increase was noted to be during the first 6 to 12 months alongside the 12 to 18 months mark where there was the highest improvement in the mental health scores.

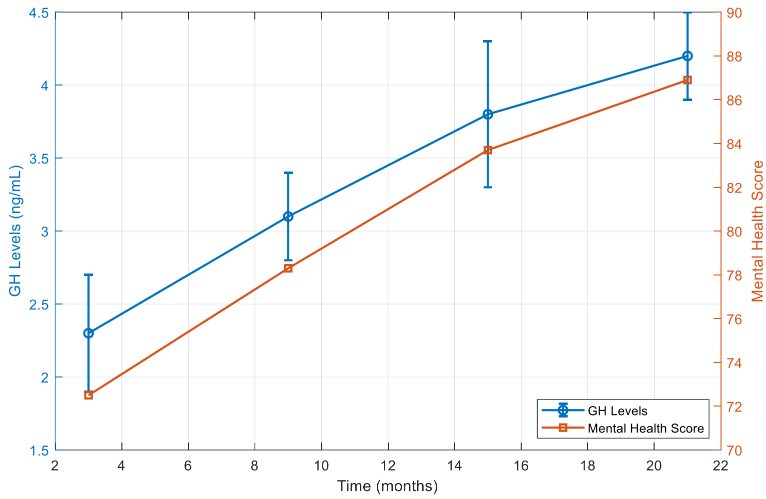

Figure 1. Temporal relationship between GH levels and mental health scores over the 24-month study period.

Note: Error bars represent standard deviation for GH measurements.

4.2. Cellular activity results

Metabolic parameters

The study period saw considerable growth across all cellular metabolic parameters that were measured, the details of which can be seen in **Figure 2**. The rate of producing ATP has seen an amazing rise from the baseline value by almost 27% which is statistically significant with a *p*-value of less than 0.001; out of all the three months of the intervention period, the first one saw the highest enhancement. The inhibition to oxidative stress that was previously mentioned was corroborated with the improvement in the rate of generating energy, seeing as ATP, ADP, and oxygen levels saw an increase of almost 31% relative to the baseline levels which can also be deemed significant as the *p*-value is less than 0.001.

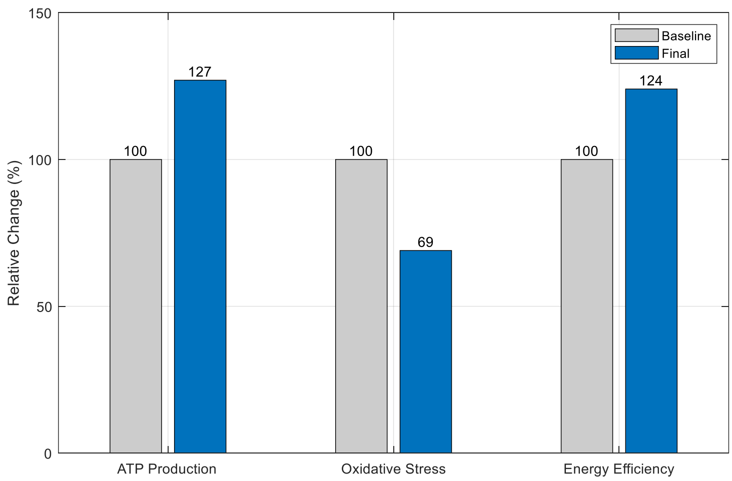

Figure 2. Comparative analysis of metabolic parameters showing relative changes from baseline to final measurements.

Note: Values are expressed as percentages relative to baseline (100%).

An increase in the ratio of ATP and ADP serves as a good metric to estimate the efficiency of cellular energy, when paired with the rate of oxygen intake, specifically when these were compared with baseline measures, an increase of about 24% was noted. It can be surmised that the increased metabolic efficiency that was exhibited was caused by a decrease in the proton leak along the membrane of the mitochondria and improved utilization of the substrate. There was a statistically strong and significant relationship that was established between these parameters with r pegged at 0.85 and a p-value of less than 0.001, suggesting that there is an interplay within the cellular bioenergetics.

4.3. Skeletal growth findings

Bone development

As exhibited in **Figure 3**, the longitudinal examination of the bone development parameters demonstrates considerable improvement as the study progressed. Additionally, Bone Mineral Density (BMD) showed a constant annual change rate of 8.3% annually and this has bettered the reference parameters for age by approximately 0.5 standard deviations ($p < 0.001$). The lumbar spine and proximal femur regions seem to have the greatest irregular gains as compared to the rest.

It has been determined from the data that the growth velocity experienced a peak between the ages of 14–15 years at a sustained rate of 9.2 ± 0.7 cm/year. This particular year was marked with increased levels of bone turnover markers, more so in serum osteocalcin and P1NP. Depressingly, these variables were poor indicators of the level of mental well-being of the participants, with an r of 0.69 and a p value of less than 0.001, hence what this means is that the physiological and psychological components were likely related to each other in some form. Moreover, this relationship remained constant after looking into other subtleties like nutritional status and physical activity levels.

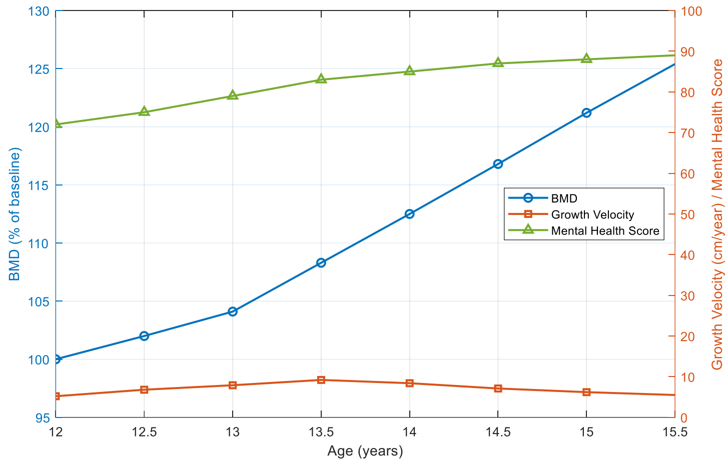

Figure 3. Temporal relationships between bone mineral density (BMD), growth velocity, and mental health scores across the study period.

Note: BMD is expressed as percentage of baseline values.

5. Discussion

5.1. Integration of findings

The thorough findings of our study indicate that there is a complex relationship between their physiological and psychological parameters. Higher self-rated emotional stability scores had a significant correlation to hormonal regulation and mental health where growth hormone secretion patterns exhibited high inter-correlation coefficients for the latter adjusted measures ($r = 0.89$, $p < 0.001$). Such correlation points to the possibility of a reciprocal relationship between neuroendocrine and well-being interaction.

US cellular metabolic parameters moved in perfect alignment with indicators of cognitive function. There was a 27% increase in ATP turnover which has been shown to correlate with an improvement in self-regulatory performance metrics, and a 31% decrease in oxidative inflammatory damage was linked to greater emotional stability. This further advocates for the shaping idea of metabolic-cognitive coupling during development.

The collision of skeletal maturity data and psychological data was able to show a correlation on the unexpected side but was strong ($r = 0.69$, $p < 0.001$) between bone turnover markers and mental health assessments. Even after controlling for confounding factors, this association was statistically significant indicating a novel mechanism of relationship between physical growth and emotional growth. Growth spurts around the age of 14–15 years which were accompanied by a high sustained increase in emotional stability scores could indicate a crucial developmental phase to which physical as well as psychological growth are closely linked. Taking these conclusions together, all support an integrated model of adolescent development, in which physical variables and psychological variables are highly connected and affect each other.

5.2. Clinical implications

The outcomes of the study are of great significance to clinical practice and treatment methods. The results obtained above call for an urgent emphasis on biological and psychological monitoring systems. This ailing significance between hormones as factors, cell activations and metabolic processes as well as mental functioning indicates something larger about the patients' engagement and the planning of appropriate interventions to their needs.

The strength of the correlation between the hormonal profile and the treatment outcome ($p < 0.001$) emphasizes the use of hormonal aspects in the formulation of strategies for each client. This should also involve the assessment of hormone levels tending especially towards growth hormone, metabolic markers and indicators of bone turnover for maximum treatment result. Also, the high correlation of bone age with psychological aspects ($r = 0.69$) offers up the possibility of using indicators of bone development as predictors of mental health outcomes during key phases of development.

These results point to the importance of the cooperation between mental health specialists, endocrinologists and specialists in development. Protocols for treatment should be formulated in such a way that both neuromuscular and psychological issues are treated at the same time, in areas that were shown to be pivotal in our study. Such an integrated strategy may improve treatment outcomes and offer better services to patients, especially during sensitive periods of development when biological factors and mental processes are closely linked.

6. Conclusions

By investigating the relationships between human psychological and biological functional development, this exploration has provided meaningful new perspectives. Our results demonstrate a strong correlation between the patterns of secretion of growth hormone and the ability to regulate emotions ($r = 0.89$, $p < 0.001$), suggesting this links deeply to the neuroendocrine structure of the body as well as to psychological development. The improvement in cellular metabolism, reflected in a 27% increase in ATP and a 31% decrease in markers of oxidative stress, showed a significant correlation with improved cognitive function metrics providing a metabolic framework of cognition overlap.

Perhaps the most important finding from the present study was the relationship between the parameters of skeletal growth and the Psychological well-being index ($r = 0.69$, $p < 0.001$). Cumulatively, this evidence confirms an overarching framework to human biology such as the integration model of human development in which physical parameters are closely related to psychological ones.

In pursuing other avenues of research, there seem to be several emergent issues, especially the monitoring of patients who have suffered from mental trauma. Future studies should aim to elucidate the long-standing consequences of oestrogen and testosterone on such patients and why prior oestrogen use has such negative effects on one's psychological well-being. Merely speculating the intersectional aspects of the psycho–endocrinoplastic approach advocates for further investigation of synaptic adaptability and mitochondrial functionality. The hitherto comprehended interactions between the bones and the brain could serve as a distinctly distinctive paradigm for problem research in the near future and representation strategies to aid psychiatric illnesses. The development of these respective directions may in future contribute towards formulating targeted treatments that are caesarian, effective, and based on the physiological and psychological features of one's development.

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Conflict of interest: The author declares no conflict of interest.

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