Investigating the link between Elite-level gymnastics and short stature

VARSHA JAYASANKAR
Integrated Science Program, Class of 2018, McMaster University

SUMMARY

Women's artistic gymnastics is one of the most popular spectator sports at the Olympic Games. Artistic gymnasts compete in two streams–elite, regulated at the international level with ~40 hours/week of training and interclub, regulated at the national level with ~20 hours/ week of training. Noticeable physical features of gymnasts include short stature and short limbs. Height data of gymnasts from the 2012 Olympic Games, 2016 Olympic Games, and 2016 NCAA Gymnastics Championships were collected and analyzed to determine whether elite gymnasts were significantly shorter than interclub and non-gymnast counterparts. Elite gymnasts at both Olympic Games were significantly shorter than interclub gymnasts at the NCAA Championships ($p<0.0001$). Additionally, gymnasts from each nation were significantly shorter than the national average height from females ($p<0.05$). Furthermore, a literature review analyzed physiological and osteological mechanisms behind the differences in stature. Female gymnasts show reduced levels of 17-β-estradiol, luteinizing hormone (LH), and follicle-stimulating hormone (FSH), critical growth hormones in female development. High prevalence of growth plate injuries in the olecranal, patellar and tarsal regions of gymnasts suggest a potential mechanism for shortened limbs in gymnasts. Height data of gymnasts who competed at both the 2012 and 2016 Olympic Games determined that more than 50% of returning competitors displayed growth, and gymnasts who took a lengthy (1+ year) break from gymnastics demonstrated growth.

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INTRODUCTION

Artistic gymnastics is one of five disciplines within the sport of gymnastics recognized by the Fédération Internationale de Gymnastique (FIG). It is one of the most popular spectator sports at the Olympic Games. In women's artistic gymnastics, athletes compete in four different apparatus–vault, uneven bars, balance beam and floor–performing short (30 to 90s) routines on each. These routines require a combination of strength, flexibility and agility to complete the mandatory movements (Girinov, Parry and Girginov, 2004).

A noticeable fact about Olympic gymnasts are their short statures. The most decorated gymnast at the 2016 Olympic games, Simone Biles, stands at 4'8" (142.24 cm). Past gymnastics stars Nadia Comaneci, gold medallist at the 1976 Olympic Games, and Mary Lou Retton, gold medallist at the 1984 Olympic Games, stood at 4'10" (147.32 cm) and 4'9" (144.78 cm), respectively (De Benito Sanz et al., 2016)

The petite heights of Olympic gymnasts have caused many controversies over the past 30 years. A gymnast must be 16 years of age by the end of the calendar year to compete at international competitions such as World Championships or Olympic Games. The small statures of some gymnasts cause them to appear younger than 16, casting doubts on whether age falsification has occurred. At the 2008 Olympics, the ages of four Chinese gymnasts was brought into questions, after all were said to be 16 but were less than 145 cm in height. After investigation, it was determined that all gymnasts were of their reported age (Macur, 2008).

Not all gymnasts are of short stature. Two-time Olympic champion Svetlana Khorkina was 165 cm tall at the peak of her career. Five gymnasts at the 2016 Olympic games were Khorkina's height or taller (International Olympic Committee, 2016). This study investigates whether elite female artistic gymnasts are significantly shorter than their non-elite and non-gymnast counterparts. Furthermore, an analysis of relevant literature will determine the ecological, hormonal and physiological causes behind short stature in female artistic gymnasts.

BACKGROUND

FEMALE GROWTH AND MATURATION

Puberty is the process by which hormonal changes signal a child's body to undergo physical transformations to mature into an adult with sexual reproduction capabilities. Females begin puberty at approximately age 10; the process is completed around age 16 (Kail and Cavanaugh, 2008). Puberty is regulated by hypothalamic–pituitary–gonadal axis and is initiated in the hypothalamus through the secretion of gonadotropin-releasing hormone (GnRH) at increasing levels (Millar et al., 2004). A possible mechanism from GnRH increase is through the increase of leptin, the satiety hormone.

In addition to the characteristic physical changes such as large growth spurts and development of feminine or masculine body types, puberty is also defined by behavioural changes–one such change in increased nutritional and food intake. Increased intake, especially with regards to fats, results in an increase in leptin release (Clavien, Theintz, Rizzoli and Bonjour, 1996). Leptin receptors that initiate the production of GnRH are located in the hypothalamus (Meister and Hakansson, 2001). Via the hypophyseal portal system, a network of blood vessels, GnRH travels from the hypothalamus to the anterior pituitary and binds to receptors on secretory cells, which in turn release luteinizing hormone (LH) and follicle-stimulating hormone (FSH) (Charlton, 2008).

LH and FSH are two critical hormones in female development. LH supports the theca folliculi, a layer of the ovarian follicle, which are responsible for the production of 17-β-estradiol precursors. FSH initiates follicular growth especially in oocyte precursors (granulosa cells). Both of these actions are part of a positive feedback loop and result in an increase in estrogens. This in turn allows for greater expression of LH, allowing for more 17-β-estradiol. The development of secondary sex characteristics, vertical growth and changes in body shape are driven by the estradiols. This positive feedback loop continues until the follicle has fully matured, at which point, 17α-hydroxyprogesterone inhibits the production of estrogens (Mahesh, 2011).

Another hormone that plays an important role in childhood growth is Insulin-like growth factor-1 (IGF-1), a hormone with similar structural features as insulin. Newborns diagnosed with IGF-1 deficiency are 2-10cm smaller than healthy babies, and present growth-relat-ed defects such as smaller extremities and heads (Lar-on, 2001). Additionally, the use of IGF-1 as a growth promoter resulted in an increase of in mean growth velocity from 3–4.7 cm/year to 8.2–9.1 cm/year. IGF-1 binds to its specific receptor (IGF1R), which initiates intracellular signaling and activates the AKT signaling pathway. This pathway is a stimulator of cell growth and proliferation. Specifically, with regards with human growth, IGF-1 is responsible for the large growth spurts during puberty. It allows long bones, such as the femur and, and soft muscle tissues to grow (Soliman et al., 2014). Production of IGF-1 is controlled by human growth hormone (hGH). hGH, also known as somatotropin, is produced in the anterior pituitary gland and released into the bloodstream, reaching the liver for IGF-1 production (Yakar et al., 2002). Stress and reduced concentrations of sex hormones inhibit hGH, which in turn inhibits IGF-1 and reduces skeletal and muscular growth (Caine et al., 2001) especially from an auxological perspective. The objective of this review is to determine if gymnastics training inhibits growth of females.

Adrenarche is period of the growth that precedes puberty, occurring between ages 7 and 10. During this stage, the adrenal cortex secretes increased levels of androgens such as dehydroepiandrosterone (DHEA) and dehydroepiandrosterone sulfate (DHEA-S) (Parker, 1993). These hormones are responsible for adolescent changes such as public and axillary hair, body odour and mild acne. DHEA has also been proven to be a partial agonist of estrogen receptors ERα and ERβ, causing similar growth effects as estradiol (Webb et al., 2006).

LEVELS OF GYMNASTICS

Women's artistic gymnastics in the United States, Canada, Great Britain and Australia can be divided into two different streams–Elite and Interclub. Gymnasts in the Elite stream intend to compete internationally (including but not limited to world championships and Olympic Games), while Interclub gymnasts limit their competition to the national level. The two streams differ in numerous ways, including but not limited to regulatory body, hours of training, scoring systems and routine composition.

Elite gymnastics is regulated by the FIG. Therefore,

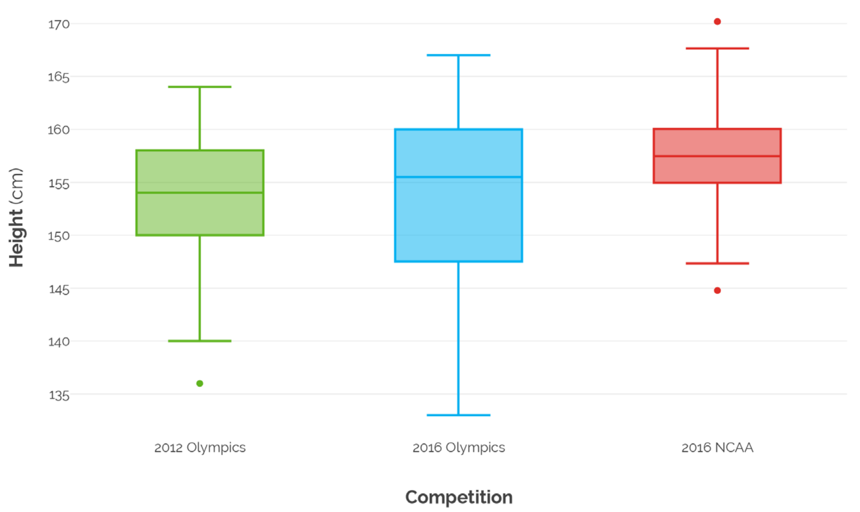

Figure 1: Heights of female artistic gymnasts in elite (2012 and 2016 Olympics, n=60 for each) and interclub (2016 NCAA Championships, n=66) level competitions. All three sets of heights are normally distributed, as per the Shapiro-Wilk test. At the 2012 Olympic Games, the mean was 153.45 cm, with a standard deviation of 6.09. At the 2016 Olympic Games the mean was 153.75 cm, with a standard deviation of 7.82. The heights of gymnasts at the 2016 NCAA Gymnastics Championships had a mean of 158.07 cm with standard deviation of 5.24.

there is uniformity in the rules, regulations and requirements that these gymnasts are held to at an international level. Gymnasts at this level, are scored using an open-ended system, regulated by the Code of Points. There are two components to this scoring system–an open-ended difficulty score and an execution score out of 10. Because of this scoring system, elite gymnastics gives preference to difficult skills (Fédération Internationale de Gymnastique, 2016a). A recommended training plan for elite gymnasts consists of two workouts per day (2-3 hours in the morning, 3-4 hours in the afternoon), 6 days week. This results in 30-42 hours/week of training (Georgopoulos, 2002).

Interclub gymnastics typically consists of multi-level program, regulated by national governing bodies. Scoring in this stream is usually out of 10, with the maximum score assigned to a perfect routine. Because of the difference in scoring in this stream, quality of gymnastics is emphasized over difficulty. Gymnasts competing at the maximum level of Interclub streams train 18-25 hours per week, on average (USA Gymnastics, 2017). In the United States, gymnasts at this level train with the goal of athletic scholarships and the possibility to compete in post-secondary competitions as a part of the National Collegiate Athletic Association (NCAA). At this level, training is regulated to a maximum of 20 hours/week (National Collegiate Athletic Association, 2015).

HEIGHTS OF GYMNASTS

To determine if elite female artistic gymnasts are shorter than interclub and non-gymnast counterparts, height data of all gymnasts competing in the team event at the 2012 and 2016 Olympic Games were collected from the London 2012 and Rio 2016 websites (International Olympic Committee, 2012; 2016). The heights were separated by National Olympic Committee (NOC, the International Olympic Committee designation for nations or territories). Using the roster data from the 2016 NCAA Gymnastics Championships, height data for collegiate gymnasts were also collected, separated by school (National Collegiate Athletic Association, 2016). NCAA gymnast heights are representative of interclub gymnast heights. Statistical analyses were completed using GraphPad InStat 3.1 (Motulsky et al., 2017). Normality for all three data sets were assessed using the Shapiro-Wilk test, with a 5% significance level.

The heights of female artistic gymnasts at the 2012 Olympic Games (n=60) was normally distributed with mean 153.45 cm, and standard deviation of 6.09. The heights of female artistic gymnasts at the 2016 Olympic Games (n=60) was normally distributed with mean 153.75 cm and standard deviation of 7.82. Combining both Olympic Games (n=120), the mean was 153.6 cm with a standard deviation of 6.95. The heights of gymnasts at the 2016 NCAA Gymnastics Championships (n=66) was normally distributed with a mean of 158.07 cm and standard deviation of 5.24. An ANOVA was completed to determine significant difference between the three groups of gymnasts (Figure 1).

The heights of gymnasts from each NOC at both Olympic Games (n=5 for each NOC, 12 NOCs competed at each Olympic Games) were compared with the national average using one sample t-tests. All NOC means were significantly smaller than the national average (Figure 2). The heights of gymnasts at both Olympic Games were significantly smaller than 2016 NCAA gymnasts ($p<0.0001$). NCAA gymnasts are significantly smaller than the U.S. national average height ($p<0.0001$) There was no significant difference between the two Olympic Games ($p>0.05$).

SELECTION BIAS

It is believed that elite gymnasts are smaller than their

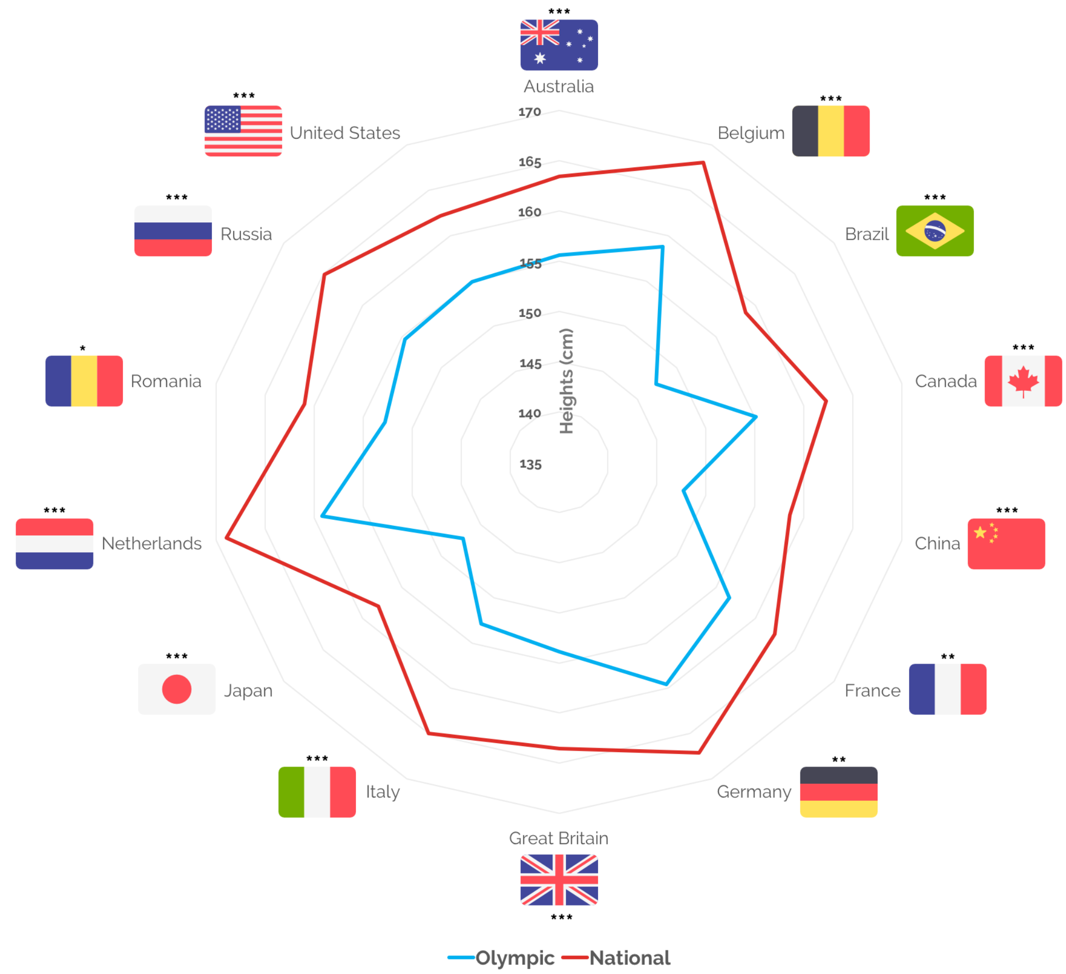

Figure 2: Comparison of average Olympic gymnast and national female heights for all nations that participated in the team competition at the 2012 and/or 2016 Olympic Games. Australia, Belgium, Netherlands, and Romania competed at one Olympic Games (n=5), while the other nations were represented at both (n=10). All nations had significant differences between national and Olympic average heights. The asterisk above or below the national flags indicate the level of significance: * (p<0.05), **(p<0.01), ***(p<0.001).

interclub counterparts due to a directional selection (Malina et al., 2013). In 2009, there were 4932 female gymnasts in the United States competing at the maximum interclub level (level 9 and 10). Only 79 (1.9%) of these gymnasts were classified as elite (USA Gymnastics, 2009).

Based on the data above, it was determined that there is a significant difference between the heights of NCAA and Olympic gymnasts, with the latter being smaller. Only 19% of NCAA gymnasts fall below the average height of Olympic gymnasts. Of the gymnasts that did fall below the Olympic average height, 50% were classified as and/or competed elite for a minimum of one season in their interclub career (USA Gymnastics, 2016). In contrast 77% of Olympic gymnasts fall below the average height of NCAA gymnasts. This data suggests that elite gymnastics, in a sense, selects for shorter gymnasts.

Studies in other countries have also determined a potential selection towards shorter heights in elite gymnasts. A sample of Polish elite gymnasts (n=5) were, on average, shorter than their counterparts who dropped out (n=4), although the difference was not significant. These height difference continued into late adolescence and full maturation, but were still not significant (Malina et al., 2013). In a study of Swiss elite gymnasts, dropouts (n=12) were significantly taller than their elite counterparts (n=12) (Tönz, Stronski and Gmeiner, 1990). A similar result was observed in a Belgian and Canadian study (Claessens and Lefevre, 1998; Lindner, Caine and Johns, 1991).

ENDOCRINE AND NUTRITIONAL FACTORS

In addition to a selection pressure that results in overall short stature in gymnastics, endocrine and nutritional factors may also play a role in these physiological differences. Female athlete triad is disorder characterized by the presence of three conditions–reduced caloric intake (negative energy threshold), amenorrhea (absence

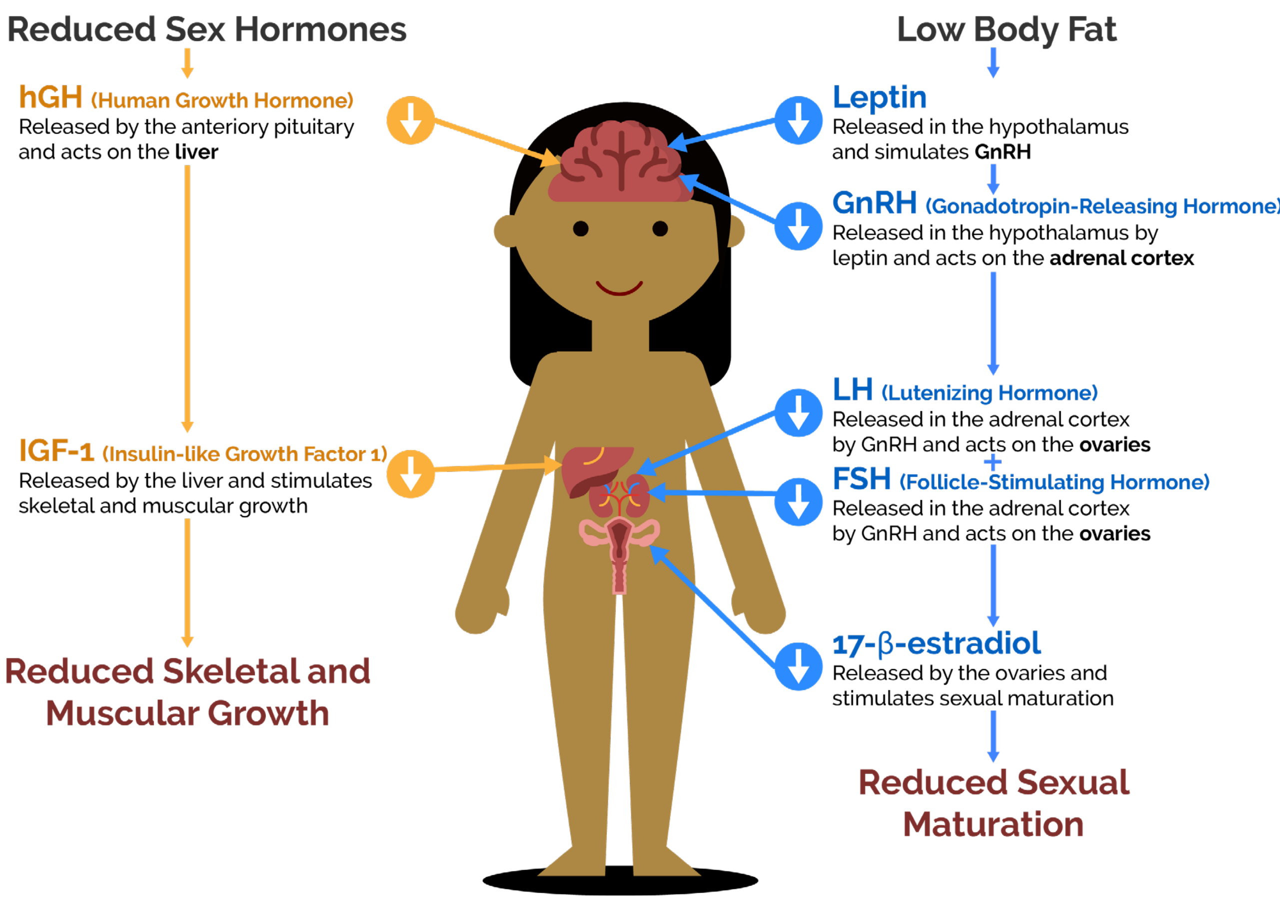

Figure 3: Endocrine pathways altered in female artistic gymnasts compared to non-athlete counterparts that affect stature and maturation. On the left is the hGH-IGF-1 system which overall reduces skeletal and muscular growth, resulting in reduced stature. The hypothalamic–pituitary–gonadal (HPG) axis is presented on the right; this results in reduced sexual hormones and maturation. The two pathways are interconnected as the reduction in sex hormones in the HPG-axis activates the hGH-IGF-1 system.

of menstruation), and low bone mineral density. The disorder is most prevalent in sports that emphasize small stature, low body weight, or leanness. When an athlete is diagnosed with one of the three characteristic conditions, it is highly likely that she is suffering from the other two (Weimann, 2002). The prevalence of this disorder is approximately 31% in female artistic gymnasts–much greater than the general population (<5%) (Buck, Bretz and Towns, 2008). These results are based on a self-reported survey of gymnasts–actual numbers could be much higher. Negative energy thresholds can delay growth and the onset of puberty, while amenorrhea alters gonadal hormone secretion, altering the levels of growth hormones including FSH and LH (American College of Sports Medicine, 2007).

Intensive gymnastics training, correlating to that of the elite level, in combination with a negative energy threshold has been determined to be inhibitory on the hypothalamic-pituitary-gonadal axis in female artistic gymnasts (Theintz, 1994). In menstruating adults, a negative energy threshold has been associated with decrease and disruption of LH release. Additionally, an experimental exercise program on post-menarcheal females increased LH disruption during periods of negative energy (Loucks, 2006). These trends however, have not yet been observed on maturing female athletes.

In a sample of 83 pre-pubescent athletes, 46 gymnasts and 37 swimmers, there were no differences in 17-β-estradiol, DHEAS, LH, and FSH levels. A similar result was observed in early pubertal gymnasts. Comparing a sample of early pubertal girls (n=12) with ectomorphic body types with gymnasts of the same age (n=12), the latter group had lower LH and 17-β-estradiol, but higher FSH levels (Peltenburg et al., 1984). Female artistic gymnasts typically have very low body fat levels, which in turn can reduced leptin levels. A decrease in leptin release reduces the production of GnRH in the hypothalamus (Meister and Hakansson, 2001), which in turn reduces the levels of FSH and LH in the body. Overall, a decrease in FSH and LH is associated with a lack of growth (Mahesh, 2011).

IGF-1 levels are also affected in female artistic gymnasts. In a sample of elite level gymnasts (n=16), measured serum IGF-1 levels were lower than normal ranges for females of that age. These gymnasts participated in a 3-day period of intensive exercise consisting of ~5 hours of gymnastics training and ~3 hours of general athletic training. During this training period, the gymnasts showed a decline in IGF-1 levels compared to the basal values. These measured levels were also lower than the controls (non-gymnasts of the same age) used in this study. Reduced levels of critical hormones in the hypothalamic-pituitary-gonadal axis suggest that puberty and adolescent development may be delayed female artistic gymnasts (Jahreis et al., 1991). Reduced IGF-1 levels result in reduced skeletal and muscular growth, which in turn could result in short stature (Caine et al., 2001) especially from an auxological perspective. The objective of this review is to determine if gymnastics training inhibits growth of females. (Figure 3).

BONE DEVELOPMENT

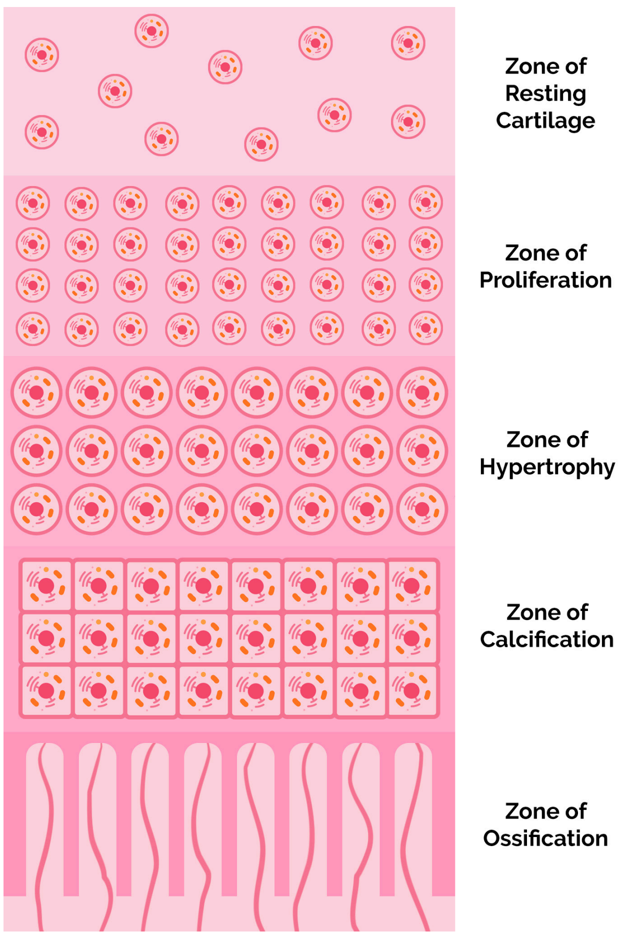

Figure 4: The five zones of osteogenesis at an epiphyseal plate. The zone of resting cartilage is located closest to the head of the bone, while the zone of ossification is located closest to the diaphysis, or midsection of the bone.

Endocrine pathways such as the hGH-IGF-1 system described above are not the only physiological cause of short stature–skeletal impacts may also carry an important role. Long bones are one of five types of bones, characterized by the fact that they are more long than wide. In the human body, the long bones are located in the legs (femora, tibiae, and fibulae), the arms (humeri, radii, and ulnae), the hands (metacarpals and phalanges), the feet (metatarsals and phalanges), and the collar bones (clavicles). These bones compromising half of human height–the other half comes from the vertebrae and the skull.

Osteogenesis, or bone growth, occurs through the addition of cells and tissue at the epiphyseal (growth) plates, a layer of hyaline cartilage at the ends or epiphysis of long bones. The epiphyseal plates have two sides–an epiphyseal side which is closer to the head or a diaphyseal side which is closer to the main body of diaphysis of the bone. Each plate contains five zones relating to growth. The zone of resting cartilage, which is nearest to the epiphyseal side of the plate, contains chondrocytes that do not rapidly divide, but bind to the epiphysis. The zone of proliferation is new cartilage is formed through rapid mitosis of the chondrocytes. These chondrocytes mature and enlarge in the zone of hypertrophy. The zone of calcification, which is nearest to the diaphyseal side contains ossified bones with blood vessels. As bones reach adult size, the epiphyseal plate is ossified and closes, ceasing growth. This occurs anywhere between ages 12 and 25 (Gilbert and Singer, 2003) (Figure 4).

EFFECTS ON VERTICAL GROWTH

Injuries, especially fractures, to the epiphyseal plate can have a negative effect on bone growth. Epiphyseal fractures result in a joint cavity between the epiphysis and diaphysis, preventing osteogenesis from occurring. This can result in shorter than normal limbs. Fractures to epiphyseal plates are referred to as Salter-Harris fractures (Salter and Harris, 2001). Sever's Disease is a condition caused by inflammation of the epiphyseal plate of the calcaneus, typically as a result of activity that involves walking, running or jumping (Scharfbillig, Jones and Scutter, 2008).

Growth plate injuries are common in elite gymnasts. In a study of 349 Australian gymnasts (151 elite, 198 non-elite), over 50% reported injuries to long bone joints. While only 12.3% reported injuries to growth plates, it should be noted that nearly 25% of elite gymnasts reported this type of injury. Only 2.6% of non-elite gymnasts reported a growth plate injury. Growth plate injuries were the most commonly reported type of injury in elite gymnasts in this study (Kolt and Kirkby, 1999). A similar study was completed in the United States, where radiographic images of non-elite gymnasts' wrists were taken to assess the impact of gymnastics training on the distal radial epiphyseal plate. Of the 44 participants, 11 showed signs of stress injuries in the growth plates (DiFiori et al., 1997).

Female artistic gymnasts have been identified for having short limbs, relatively short legs for height or stunted growth of the legs (Buckler and Brodie, 1977).

Table 1: Height differences of gymnasts who competed at both the 2012 and 2016 Olympic Games

Gymnast	Height (2012, cm)	Height (2016, cm)	Change in Height	Age (in 2012)
Black (CAN)	155	155	0	17
Bui (GER)	155	155	0	19
Douglas (USA)	150	157	7	17
Fasana (ITA)	152	155	3	16
Ferlito (ITA)	157	160	3	17
Ferrari (ITA)	146	146	0	21
Hypólito (BRA)	147	147	0	28
Mustafina (RUS)	161	162	1	18
Paseka (RUS)	159	161	2	17
Raisman (USA)	157	157	0	18
Seitz (GER)	162	162	0	19
Rogers (CAN)	157	165	8	19
Teramoto (JPN)	136	141	5	17
Average	**153.38**	**155.62**	**2.23**	**18.54**

Growth plate injuries cause a temporary detachment of epiphysis from the diaphysis which prevents bone growth and can result in shorter limbs (Gilbert and Singer, 2003). These types of injuries are prevalent in elite and non-elite gymnasts. Therefore, it is possible that the short limbs and subsequent shorter heights of female artistic gymnasts can be a caused by growth plate stress and/or injury.

DELAYED GROWTH

Elite gymnastics training may impact female height through hormonal and physiological changes. However, numerous studies indicate that elite gymnastics training delays the onset of puberty, and still allow normal pubertal growth. In a longitudinal study of female gymnasts, concentrations of 17-β-estradiol and LH were lower than the reference sample for 9-13 year olds, but showed later increases which were consistent with delayed maturation (Tönz, Stronski and Gmeiner, 1990).

Of the 120 gymnasts that competed in the team event at the 2012 and 2016 Olympic Games, 13 competed at both (Table 1). All but one of these gymnasts were past the normal age of puberty (16 years), and all but one were below the maximum age of epiphyseal plate ossification (25 years). Seven of these 13 gymnasts increased in height between the two Olympic Games, with the average increase in height of 4.14 cm. All but 2 gymnasts under the age of 19 showed growth between the two Olympic Games.

Research has also determined that cessation of gymnastics training for prolonged period of time can trigger the onset of puberty and/or growth spurts. In a longitudinal study of 21 Australian female gymnasts, it was determined that a lower than normal growth rate could be associated with gymnastics training. Among with sample, 4 gymnasts retired from the sport at approximately age 11. Height velocities in these former gymnasts accelerated substantially, which was interpreted by the authors as catch-up growth caused by the cessation of training (Bass et al., 2000).

Of the 13 gymnasts that competed at both Olympic Games, three have publically stated that they had ceased elite gymnastics training for more than 1 year–Gabrielle Douglas (USA), Alexandra Raisman (USA) and Brittany Rogers (CAN). Both Douglas and Raisman took a break from elite competition between the 2012 Olympic Games and the 2015 competition season, completely ceasing gymnastics training between August 2012 and January 2015. Rogers did not fully cease gymnastics training–she trained and competed at the NCAA level with lesser hours than her elite regimen. Raisman showed no change in height between the two Olympic Games. Douglas and Rogers however, showed an increase of 7 and 8 cm, respectively, the highest of the 13 gymnasts.

Another case of delayed growth in elite gymnasts can be seen in Kyla Ross (USA). Ross, then 15 years old, competed at the 2012 Olympic Games, measuring 157 cm. Ross continued to compete at the elite level until 2016, when she switched to training at the interclub level in preparation for NCAA competition. During the time between her retirement from elite gymnastics in January 2016 to her enrollment as a freshman at University of California Los Angeles (UCLA) in September 2016, Ross experienced a large growth spurt. According to UCLA's roster, Ross now stand 5'7" (170.2 cm), a 13-cm growth between the two Olympic Games (National Collegiate Athletic Association, 2016). Overall, the high prevalence for delayed growth spurts in elite gymnasts, and larger growth spurts during periods of suspended training, suggest that training at the elite level may postpone normal pubertal developments in female gymnasts.

ADVANTAGES OF SHORT STATURE

Overall elite gymnasts are indeed shorter than their interclub and non-athlete counterparts–this difference in stature provides them with a biomechanical advantage. A short stature provides gymnasts with increased rotation power. In a longitudinal study of 37 gymnasts over 3.3 years, it was determined that gymnasts with a lower growth rate have a higher strength to mass ratio, increasing their potential to perform full-body rotations. Gymnasts with higher growth rates have better performance on back rotation skills, but are lacking in side and front rotational skills, as well as vertical jumps. Skills in gymnastics emphasize rotation around the all body axes–frontal, longitudinal and sagittal. Elements of increasing difficulty involved rotation around multiple axes at the same time (Ackland, Elliott and Richards, 2003).

A gymnasts' balance is also impacted by stature. A person's centre of gravity is approximately below the navel. A shorter gymnast, therefore has a centre of gravity that is closer to the ground. In a 2007 study of collegiate gymnasts and basketball players, gymnasts had superior static and dynamic balance abilities than basketball players. For reference, the average height of a collegiate basketball player is 6'6" (198 cm), while the average collegiate gymnast stands at 5'2" (158 cm). While centre of gravity has some effect on this result, the focus of the individual athlete's training can also have an impact. For example, basketball players rarely balance motionless on one leg, while this is quite common for gymnasts (Bressel et al., 2007).

A short stature also helps gymnasts navigate and manipulate the four pieces apparatus in women's artistic gymnastics. As per FIG regulations the diagonal distance between the uneven bars must be between 130 and 180 cm. For a taller gymnast, a 180 cm gap may interfere with their ability to complete giant swings, 360º rotations around the high bar; a smaller gap can exaggerate this disadvantage further. Should their feet hit the low bar during rotation, it can cause injury and the gymnast will receive a mandatory deduction during competition. On the floor exercise, the diagonal distance is 1697 cm; a shorter gymnast can complete more somersaults and handsprings within this distance, while a taller gymnast has a higher chance of landing out-of-bounds and incurring a deduction. Similarly, the length of the balance beam (500 cm) provides the smaller gymnast the advantage, as she will be able to complete more saltos (Fédération Internationale de Gymnastique, 2016b).

CONCLUSION

Across the world, elite female artistic gymnasts are significantly shorter than their non-elite and non-gymnast counterparts. Gymnasts at the 2012 and 2016 Olympic Games were on average, shorter than gymnasts that competed at the 2016 NCAA Gymnastics Championships. Between interclub and elite gymnasts, a directional selection towards smaller heights may be present, as a larger percentage of elite gymnasts are shorter than their interclub counterparts. Endocrine effects may explain the differences in height of elite gymnasts, as they showed reduced concentrations of hormones in the hypothalamic-pituitary-gonadal axis that control puberty and growth. Additionally, epiphyseal plate fractures, injuries and stress may stunt limb growth, affecting a gymnast's vertical height. While elite gym-nasts at the Olympic Games are short, some show delayed growth compared to normal puberty standards, or growth during cessation of training regimens.

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