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Adult height prediction of young handball players and combat sport athletes - does making weight influence the adult height?

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Abstract

Background: Combat sports athletes are known to regularly participate in rapid weight loss practices and to restrict their caloric intake. These restrictions might negatively influence the growth during adolescence.

Objective: The aim of this thesis was to verify if the predicted adult height of youth combat sports athletes and handball players, match their actual body height as grown-ups and to analyse differences between these groups.

Methods: The predicted height, using the Tanner-Whithouse Mark II or Tanner-Whitehouse 3 method, and the actual adult height of 22 female and 23 male handball and combat sports athletes (CS), including Judo, Kickboxing and Taekwondo athletes, was retrospectively statistically analysed.

Results: No significant difference was found between the predicted adult height and the actual adult height in all groups with handball players (all: -0.8 ± 2.1 cm, p = 0.062, f: -1.0 ± 2.0 cm, p = 0.071, m: -0.6 ± 2.4 cm, p = 0.437) and in the group of female combat sports athletes (-0.9 ± 1.9 cm, p = 0.313). A significant difference was found for all female athletes (-0.9 ± 1.9 cm, p = 0.032) and for groups including the male combat sports athletes (all: -1.2 ± 2.6 cm, p = 0.003, all m: 1.5 ± 3.2 cm, p = 0.033, all CS: -2.0 ± 3.2 cm, p = 0.024, m CS: 2.6 ± 3.7 cm, p = 0.045). The intergroup analysis of the differences between predicted and actual adult height indicated no significant difference but a medium to large effect size between the male handball players and male combat sports athletes (g = -0.65, p = 0.134).

Conclusion: The Tanner-Whithouse Mark II and Tanner-Whitehouse 3 methods are accurate in predicting the height of handball players and female combat sports athletes but not the height of male combat sports athletes. The smaller actual adult height of the combat sports athletes indicates some negative influence on their growth during adolescence, likely due to weight making practices. Further studies under standardised conditions are needed for firm evidence on the reasons for a smaller adult height as well as adequate screening tools for early interventions.

Zusammenfassung

Hintergrund: Kampfsportler*innen sind bekannt dafür regelmäßig an Praktiken zur schnellen Gewichtsabnahme teilzunehmen und ihre Kalorienaufnahme einzuschränken. Diese Praktiken und Einschränkungen können möglicherweise das Wachstum während der Adoleszenz beeinflussen.

Ziel: Das Ziel dieser Masterarbeit war es zu verifizieren, ob die vorhergesagte Körpergröße als Erwachsener von jugendlichen Kampfsportler*innen und Handballer*innen mit der tatsächlichen ausgewachsenen Körpergröße übereinstimmt und Unterschiede zwischen diesen Gruppen zu analysieren.

Methodik: Die vorhergesagte Körpergröße, die mittels der Tanner-Whitehouse Mark II und Tanner-Whitehouse 3 Methode gewonnen wurde, und die tatsächliche ausgewachsene Körpergröße von 22 weiblichen und 23 männlichen Handballer*innen und Kampfsportler*innen (KS) wurde retrospektiv statistisch analysiert. Kampfsportler*innen in dieser Studie üben die Sportarten Judo, Kickboxen und Taekwondo aus.

Ergebnisse: Kein signifikanter Unterschied zwischen der vorhergesagten und der tatsächlichen Körpergröße wurde in den Gruppen der Handballer*innen (alle: $-0,8 \pm 2,1$ cm, $p = 0,062$, w: $-1,0 \pm 2,0$ cm, $p = 0,071$, m: $-0,6 \pm 2,4$ cm, $p = 0,437$) und in der Gruppe der weiblichen Kampfsportler*innen ($-0,9 \pm 1,9$ cm, $p = 0,313$) gefunden. Ein signifikanter Unterschied wurde gefunden für alle weiblichen Athletinnen ($-0,9 \pm 1,9$ cm, $p = 0,032$) und alle Gruppen, die die männlichen Kampfsportler beinhalten (alle: $-1,2 \pm 2,6$ cm, $p = 0,003$, alle m: $1,5 \pm 3,2$ cm, $p = 0,033$, all KS: $-2,0 \pm 3,2$ cm, $p = 0,024$, m KS: $2,6 \pm 3,7$ cm, $p = 0,045$). Kein signifikanter Unterschied wurde im Vergleich der Differenzen zwischen vorhergesagter und tatsächlicher Körpergröße zwischen den Gruppen gefunden. Allerdings konnte eine mittlere bis große Effektgröße ($g = -0,65$, $p = 0,134$) für den Vergleich zwischen den männlichen Handballern und männlichen Kampfsportlern gefunden werden.

Schlussfolgerung: Die Tanner-Whitehouse Mark II und Tanner-Whitehouse 3 Methoden sind akkurat in der Vorhersage der erwachsenen Körpergrößen von Handballer*innen und weiblichen Kampfsportlerinnen, aber nicht von männlichen Kampfsportlern. Die kleinere erwachsene Körpergröße von männlichen Kampfsportlern deutet auf negative Einflüsse auf das Wachstum während der Adoleszenz hin, wahrscheinlich durch Praktiken zur schnellen Gewichtsabnahme und eingeschränkte Kalorienaufnahme. Weitere Studien unter standardisierten Bedingungen sind notwendig, um feste Beweise für die Gründe einer kleineren erwachsenen Körpergröße zu finden, sowie der Einsatz adäquater Früherkennungswerkzeuge.

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1 Introduction

In many countries success in international sport competitions is considered to be very prestigious. Billions of people all over the world watch sporting events like the Olympic Games (Bountakis et al., 2018) where athletes compete against each other and, indirectly, for national success (Güllich & Cobley, 2017). Furthermore, the global sports market is a billion-dollar industry. It is expected to grow from $354.96 billion in 2021 to $707.84 billion in 2026 (Research and Markets, 2022). In 2019 the youth sports market was totalling $24.9 billion and is expected to reach $77.6 billion by 2026 (Research and Markets, 2019).

Therefore, countries all over the world have tremendously increased their investments in elite sports (Bountakis et al., 2018) as well as in talent identification and talent development programmes (Güllich & Cobley, 2017). Hence, there is an enormous pressure to find and develop young talented athletes (Wattie & Baker, 2017). Especially small countries with less financial means and a smaller population hope to find talent through these programmes in order to compete with larger nations (Matthys, 2012).

1.1 Talent identification and development

The first known study about talents in sport goes as far back as the mid 1800's by Francis Galton (Galton, 1869). However, in the last 20 years, talent identification and development became more and more important in sports (Leite et al., 2021). This search for talented young athletes is widespread over the world with increasing systematisation (Bergeron et al., 2015).

There is currently no consensual definition of what a talent is (Schorer et al., 2017). In general, a talented individual is described as a person with a certain unique aptitude (Malina et al., 2017). In sports this can be someone who shows potential for long-term success and with an outstanding skillset that differs from their peers (Spies et al., 2022). The recognition of these young athletes who exhibit potential to later succeed in elite sports is known as talent identification (Sarmento et al., 2018), while the process of providing athletes with learning environments that help them realise their potential is called talent development (Kelly & Williams, 2020).

Talent identification programmes try to find these talented athletes early in order to focus funding and training opportunities for optimal development of their skills (Durand-Bush & Salmela, 2001). Identification and even selection of talent can even be necessary because of limited financial and personnel resources, as well as missing facilities. It is seen as a possibility to use those already limited resources in a more efficient way (Till & Baker, 2020). However, to predict the potential of athletes at a young age is a complex and difficult process (Skorski et al., 2016), as it is multifaceted and trajectories to becoming an elite athlete vary greatly among individuals (Bergeron et al., 2015). Furthermore, research suggests that this process is imperfect at best (Baker & Wattie, 2018), which in return generates continued interest as well (Till & Baker, 2020).

Another topic that is widely discussed in the scientific community is the nature versus nurture debate. Researchers differ in their views on whether outstanding achievements of talented athletes is mainly the result of genetics and biological factors (i.e. nature), the product of learning and experience (i.e. nurture), or a mixture of both (Johnston et al., 2018).

Modern behavioural genetics has proven that many variables in which individuals can be different show a hereditary component, but the impact size can vary. These heritabilities include cognitive and physical abilities, as well as personal interests, values, and personality traits like body height, rate of maturation, aptitude, adaptations to training, game intelligence, movement proficiency, motivation and psychological skills (Baker & Horton, 2004; Bouchard, 2004; Malina et al., 2017).

Having success at the elite level in sports stems from the interaction between these heritable characteristics and environmental aspects like access, opportunity, coaches, family, and chance and vary according to the sociocultural and political-economic situation of a country (Baker & Horton, 2004). The distinction between two talents often lies in the different weighting of these abilities or traits. Since winning a gold or a silver medal may be decided by milliseconds, centimetres, one contact, or other small events, a more favourable environment or physical trait could provide the necessary competitive edge (Simonton, 2017).

Physical factors, for example, are comprised of size, physique, body composition as well as maturity status and timing. Especially growth and maturation greatly influence physical performance (Beunen & Malina, 2007) as well as psychological athletic development (Radnor et al., 2021). According to Ogura and Fujii, outstanding male and female athletes tend to be tall in many sports (Ogura & Fujii, 2018). Furthermore, a systematic review by Johnston et al. (2018), concluded that some variables like maturity level, height and other performance variables like agility, sprint speed, strength, etc. were able to discriminate between the highest skill levels. However, the review did not find a consistent relationship between these variables and predicting athletic skill levels (Johnston et al., 2018).

Additionally, in the process of talent identification, development and selective decisions concerning adolescent performances need to be made about future adult abilities (Till & Baker, 2020). Yet, these performance indicators in sports improve with growth and maturation but progress at varying rates in a non-linear fashion during childhood and adolescence (into adulthood) (Bergeron et al., 2015). However, the key factors of growth and maturation are well understood (Till & Baker, 2020).

1.2 Maturation and growth

There are three processes that characterize the span between birth and adulthood (Malina et al., 2019): The two biological processes of growth and maturation, as well as the behavioural process of development (Malina, Bouchard, et al., 2004). All three occur and interact with each other at the same time, can influence concepts of self, self-esteem, etc., and are important in talent development (Malina et al., 2019).

The process of development includes the improvement and acquisition of cognitive, emotional, social, motor, moral and other behaviours. These behaviours are expected in the culture someone is brought up in (Malina et al., 2019). Growth is defined as a measurable increase in the size of the body as well as the changes in composition, segments of the body, organs and other related systems (Malina et al., 2017, S. 150). Heart volume and mass as well as lungs and their function are related to the growth in body size and therefore crucial for physical performance. The nervous system and brain first grow at a fast pace in early life and later at a more gradual rate (Malina et al., 2017).

Maturation on the other hand is the advancement within each bodily system towards achieving biological maturity (Malina et al., 2017). It can vary in magnitude, timing and tempo between individuals and systems (Beunen & Malina, 2007; Lloyd et al., 2014). Maturation tempo is the rate at which a specific system progresses in maturation. Examples are the rate of progression of the skeletal age within a year, and how fast or slow one passes from the beginning stages of sexual maturation to a mature state. Maturity timing describes the chronological age when a certain maturation-event like the beginning of the menarche, the appearance of secondary sex characteristics, or the peak height velocity occurs (Malina et al., 2017). Individuals with the same chronological age can differ greatly in their biological maturation status and timing (Cumming et al., 2017). The chronological age is calculated as the time away from the date of birth (Lloyd et al., 2014).

Children can be either early maturers, if they are ahead in biological maturation according to their chronological age, normal or average maturers, if their maturation coincides with the chronological age, or late maturers, if they are behind in their maturation (Malina, Bouchard, et al., 2004). This variance in maturation status is affected by genetics as well as environmental factors and can vary five to six years between two persons with the same chronological age (A. Johnson et al., 2017).

The differences in timing of maturation can impact physical development, like stature, power, strength and motor performances, as well as psychological development including influences on adolescent behaviour (Cumming et al., 2017; Malina, Bouchard, et al., 2004) Therefore, the maturity status plays an important role in talent development (Malina, Bouchard, et al., 2004). Coaches should consider biological maturation in their planning of training to optimise adaptations and to prevent activity-related injuries (Lloyd et al., 2014).

Due to varying maturity statuses, differences in height and weight can be observed starting at 6 years old and continuing to increase into adulthood. Therefore, from late childhood on, early maturers are heavier and taller than their peers. Additionally, they might have a greater peak-height-velocity (PHV), which can cause a bigger increase in height, weight and lean mass during puberty (Malina, Bouchard, et al., 2004). This in return can lead to athletic advantages between the ages of 11 and 14 years. During this period especially, early maturers tend to outperform less mature athletes in speed, strength, power, agility and momentum tests (Guimarães et al., 2019; Meylan et al., 2010). In later adolescent years, the height differences between late, normal and early maturing athletes become more insignificant (Cumming et al., 2017). Lefevre et al. (1990) suggested that these advantages in performance of early maturers completely disappear at an adult age. Furthermore, late maturing boys can increase their performance between 18 and 30 years more than early maturers (Beunen & Malina, 2008).

Early maturing boys possess a more adaptive motivational profile than late maturers. They perceive themselves as more attractive, stronger, more competent in sports, more athletic and demonstrate higher self-esteem (Cumming et al., 2012; Lintunen, 1988). This leads to a higher probability of early maturing males to be selected for sports where size, speed, strength and power are favourable (Clemente et al., 2021).

The consequences of differing maturation status in females are not equivalent to those in males. Early maturing girls are taller, heavier with a more pronounced PHV as well. However, they only outperform their peers in strength tests, whereas differences in speed, agility and power tests are insignificant (Malina, Bouchard, et al., 2004). Additionally, early maturing females show a less favourable psychological profile, but this may vary in different cultures with different views of female attractiveness (Cumming et al., 2012, 2017).

These inter-individual differences in growth and maturation may lead to inequity in youth competitions and increased injury risk (Malina, 2009). Firstly, young athletes are often grouped into age graded teams or identified as talent according to their chronological age (Radnor et al., 2021). Secondly, early maturing athletes are favoured in selection processes because of their physical advantages (Till & Baker, 2020). The first bias is called the relative age effect (Kelly et al., 2020), relative age hereby refers to an athlete's chronological age within these age groups and is determined by a cut-off date. Therefore, the chronological age difference of young athletes in these groups can be a year or more (Radnor et al., 2021). The phenomenon of the relative age effect refers to the greater likelihood of athletes born at the beginning of a cut-off date to be selected into talent development programmes (Kelly et al., 2020) as they are often more mature, stronger, and faster than younger players (Musch & Grondin, 2001). Young talents born in the first quartile have a 38-40% chance to be chosen, whereas athletes in the fourth quartile have only a 15-21% likelihood (Lloyd et al., 2014). The latter effect refers to the maturity selection bias (Till & Baker, 2020). This bias is especially true for late maturing athletes (Malina, 2009).

Early maturers are more likely to be selected and identified as talents because of their physical advantages (Sherar et al., 2007). These selected athletes will usually have the possibility to play at higher levels of competition with greater resources and better conditions for skill acquisition (Helsen et al., 1998). Therefore, it is possible that early maturers are selected for specific positions even though a late maturing athlete has a greater predicted adult height and would be better suited in the future (Lloyd et al., 2014).

The challenges that arise with selecting talent is further highlighted by Ostojic et al. who analysed longitudinal data of early and late maturing football players. Their results shows that significantly more late-maturers reached the elite level than early maturing footballers (2014). This suggests that as the level of performance increases, late-maturing players are being favoured (Sarmento et al., 2018). Therefore late-maturing youth players may profit from being nurtured until they reach maturity (Meylan et al., 2010).

To counteract these biases, strategies like bio-banding are being utilised in youth sports. In bio-banding, athletes are grouped according to their maturity status instead of age groups (Cumming et al., 2017). This means that they are sorted into different bands based on their biological maturation rather than according to their physical characteristics. However, bio-banding does not consider their technical skills or psychological and cognitive maturity (Lloyd & Oliver, 2012; Malina et al., 2019). Additional maturity information might improve the process of talent identification and development (Till & Baker, 2020). To assess the athletes maturation status, several different methods are available (Malina et al., 2019) that might be directed by time or resources available (Till & Baker, 2020).

1.3 Maturity Assessment

Due to selection biases in talent selection and development, it is important to assess the maturity status of young athletes. Most of the time, chronological age is easily determined whereas the assessment of biological age is a lot more complex (Radnor et al., 2021). Several methods found in literature can be categorised into three groups, namely sexual, skeletal or somatic maturity indicators (Baxter-Jones et al., 2005).

1.3.1 Sexual Maturation

Sexual maturity refers to the changing secondary sex characteristics toward reproductive capability during the pubertal interval, such as breasts, genitalia, and pubic hair. However, assessment of these characteristics can be seen as invasive (Bergeron et al., 2015; Olivares et al., 2020) and their accuracy can vary greatly between physicians and self-assessments (Slough et al., 2013; Taylor et al., 2001).

1.3.2 Somatic Maturation

Somatic means that something relates to the musculoskeletal system (Balyi & Way, 2009), with somatic maturity referring to the extent the body stature grows (Lloyd et al., 2014). The easiest way to assess the somatic maturity uses longitudinal anthropometric data. Somatic growth proceeds nonlinear, with rapid growth phases being replaced by relative plateaus in bodily development (Stratton & Oliver, 2019). Therefore, with continuous collection of body height, an analysis of a growth curve would be possible. This curve could provide data of the beginning of growth spurts and the PHV (Radnor et al., 2021). However, identifying the age at PHV requires longitudinal data from middle childhood to late adolescence (Lloyd et al., 2014). Since this data is often not available, predictive equations can be an alternative to forecast the age at PHV using only a single measurement (Radnor et al., 2021). Mirwald et al. (2002) proposed a predictive equation based on the differential growth rates of the legs and the trunk. Long leg bones exhibit an earlier peak growth than bones of the trunk. This predictive equation requires chronological age, body height, as well as seated height and body mass (Mirwald et al., 2002). Despite its popularity, this equation has been criticised for having a low sensitivity in identifying late and early maturers (Malina & Kozieł, 2014).

Another method for the assessment of somatic maturity is the percentage of predicted adult height (%PAH). It is based on the premise that average heights of the biological mother and father, called mid-parental height, provide a range for the future adult height of the child or adolescent (Malina et al., 2019). Khamis and Roche proposed a sex-specific prediction equation. Their equation includes the mid-parental height, age specific constants for weight, and the current stature for accuracy improvement (Khamis & Roche, 1994; Malina et al., 2019). Compared to the Mirwald equation, it is better equipped to differentiate between late and early maturers and can therefore be used in bio-banding as well (Malina et al., 2019). Furthermore, it has been shown that the percentage of predicted adult height correlates with skeletal age, the gold standard for maturity estimation (Olivares et al., 2020).

1.3.3 Skeletal Maturation

Many researchers consider skeletal maturation as the best maturity indicator since it can be applied from childhood through adolescence (Beunen et al., 2011). By determining the bone age it is possible to evaluate the biological maturity as well as the mature height (Satoh, 2015). It is therefore an important part of talent identification and development (Lolli et al., 2021). The origins of bone age assessment stem from clinical practices, especially by paediatrics, to evaluate impaired or accelerated growth, short or tall stature, delayed or early puberty, and the diagnosis of other endocrine disorders and paediatric syndromes (Martin et al., 2011; Waldt et al., 2014). Furthermore, it is used in international immigration programmes to estimate the chronological age of asylum seekers without documentation (Thodberg, Kreiborg, et al., 2009).

Skeletal maturation follows the development and progression of ossification centres to fully ossified bones since these sequences and changes are predictable (Cavallo et al., 2021; Lolli et al., 2021). The bone segments start maturing in the primary ossification centre. The final shape of the bone is reached through enlargement, mineralisation and remodelling in different stages (Cavallo et al., 2021; Waldt et al., 2014). The first stage occurs before birth, during the second month of foetal development. At birth epiphyseal ossification centres of the distal femur, proximal tibia talus, calcaneus, and cuboid exist. Afterwards the ossification of the epiphyses and apophyses progress parallel to the longitudinal growth of the tubular bones (Waldt et al., 2014). These maturation processes of the epiphysis and the ossification of the epiphyseal plates, also called growth plate (see figure 1), show intra- and interindividual variations. During puberty, the epiphysis closes by melting with the diaphysis and brings the skeletal development to a close. After puberty, maturity is assessed by comparing how much of the epiphyseal fusion of the ulna and radius has already occurred (Cavallo et al., 2021; Waldt et al., 2014).

Several of the body’s bones have been studies as maturation indices. However, the wrist and the knee area showed the best results for bone age determination (Cavallo et al., 2021). Radiographs of the hand show numerous specific ossification centres that progress over time. This method is usually used in children older than 3 years old. Under the age of 3, it is common to work with radiographs of the knee as changes here can be more easily assessed than in the hand (Creo & Schwenk, 2017).

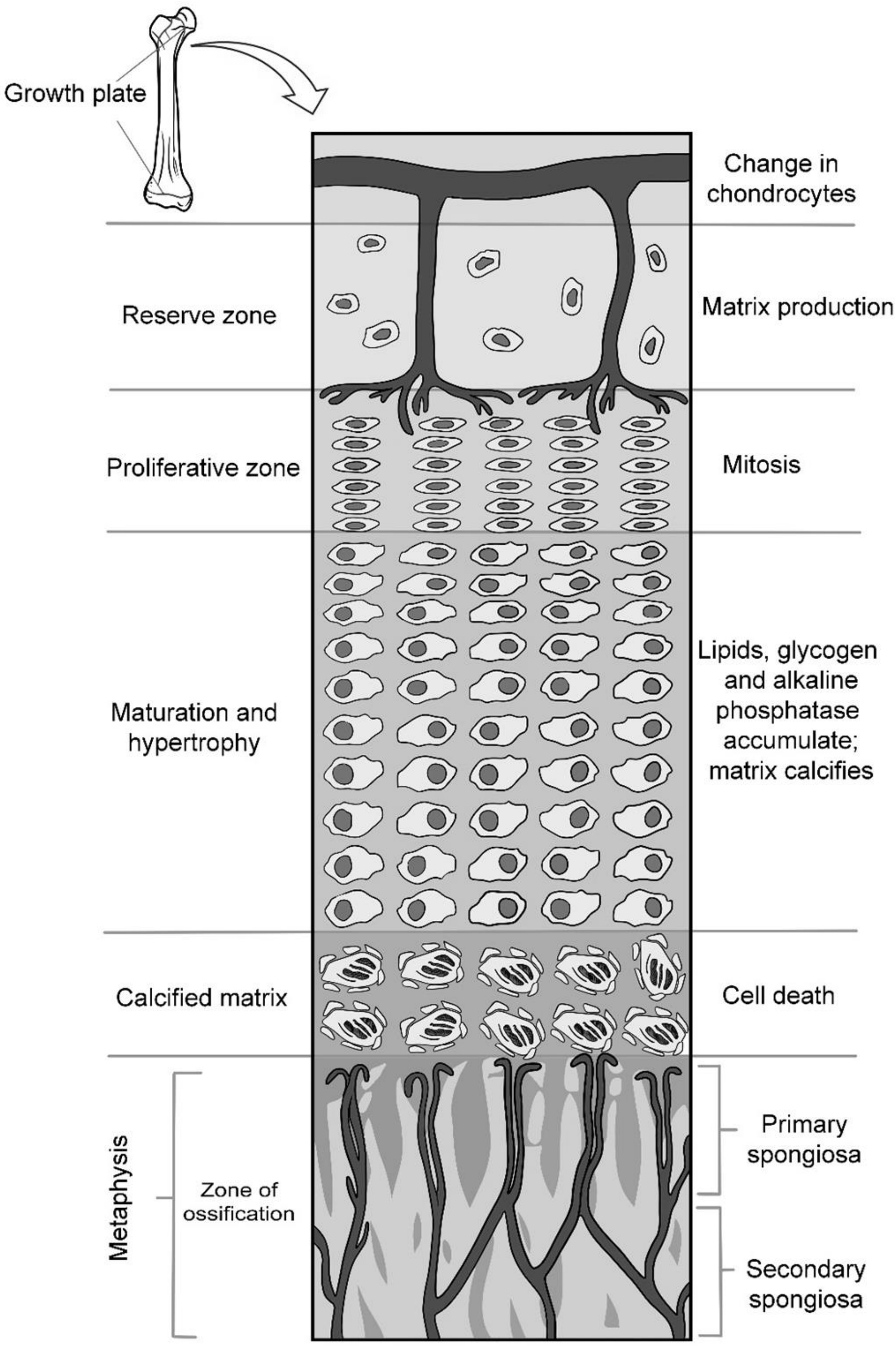

Figure 1: The growth plate or epiphyseal plate. Adapted from (Kannian & Ryan, 2019)

Usually, for bone age assessment, a radiograph of the left hand and wrist is made. The left hand is generally used, as in earlier days the usually dominant right hand was more often impaired due to farming and factory work. For reliable results it is important to adhere to a correct procedure (Cavallo et al., 2021). The arm and forearm are supposed to be in the same horizontal plane and the palm of the hand should face downwards on a rigid plane with slightly spread fingers, with the thumb in a natural position, i.e. rotated to about 30 degrees from the index finger (Cameron, 2004a; Cavallo et al., 2021).

Another aspect that should be considered when using radiographs for bone age assessment in children is the radiation dosage the children are exposed to (Lolli et al., 2021). The World Health Organisation recommended a maximum dosage of 0.5 mSv for children taking part in research projects in 1977 (Cameron, 2004a). However, the typical dosage of an x-ray of the wrist and arm is reported to be 0.001 mSv (Lolli et al., 2021) whereas the average annual radiation dosage in Austria is about 6 mSV. Though exposure may deviate significantly from this value. The predominant part of the radiation exposition can be attributed to natural radiation sources and medical applications of ionizing radiation (Ditto et al., 2022).

Assessment of radiographs to determine bone age can be done manually or with automated methods (Prokop-Piotrkowska et al., 2021). The most commonly used bone age methods are the Greulich-Pyle (GP) method (Greulich & Pyle, 1959), the Tanner Whitehouse methods 1 to 3 (TW 1-3) (Tanner et al., 2001; Tanner & Tanner, 1983; Tanner & Whitehouse, 1962), the Fels method (Roche et al., 1988) and the automated BoneXpert™ methods versions 1 to 3 (Martin et al., 2022; Thodberg, Jenni, et al., 2009), detailed below.

1.3.4 Greulich-Pyle method

In the GP method, radiographs of the hand and wrist are compared to standard radiographs in a comparison atlas to determine the bone age of the child (Satoh, 2015). This atlas technique goes back to T. Wingate Todd, who published the first such atlas in 1937 (Todd, 1937). His atlas was based on the radiographs of 1000 children from the Brush Foundation Study of Human Growth and Development in Ohio (Cameron, 2004a). Greulich and Pyle refined T. Wingate Todd's atlas using the same study of medium to high class white children and published the Greulich-Pyle Atlas (Cameron, 2004a; Cavallo et al., 2021; Thodberg et al., 2012). As an addition to the images, the GP atlas features explanations concerning gradual changes of bones at a given age. Bone age can then be calculated by comparing and matching the recorded radiographs with the most similar standards in the book (Prokop-Piotrkowska et al., 2021). This is the most popular and widely used bone age method, since it is relatively easy to learn and evaluation only needs about 1.4 minutes (Cavallo et al., 2021; Prokop-Piotrkowska et al., 2021). If, however, significant maturity differences in individual ossification centres are found, a very time-consuming bone-by-bone comparison method should be used. In this method, one needs to evaluate the long (radius and ulna) and short tubular bones (carpals and metacarpals) and therefore each epiphyseal centre is assessed separately (Waldt et al., 2014).

Even though the GP method is commonly used, it has several significant drawbacks. For instance, it shows a high inter- and intra-rater variability (Prokop-Piotrkowska et al., 2021).

In inter-observer studies the standard error on a single assessment showed a range from 0.45 to 0.83 years (Bull et al., 1999; G. F. Johnson et al., 1973; Kim et al., 2008; Roche et al., 1970; Thodberg & Sävendahl, 2010). Furthermore, there is no standardized approach on how to weigh a bone, resulting in too diverse maturity scores. Another drawback is the population the atlas is based on. Since the children used in the study were white middle- and upper-class, the data may not be valid for all populations (Prokop-Piotrkowska et al., 2021). In a meta-study by Alshamrani et al., African females showed a significantly advanced bone age and Asian boys a significantly delayed bone age between the ages of 6 and 9 and a significantly advanced one at 17 years, when compared to GP standards (2019).

1.3.5 Tanner-Whitehouse methods

In Europe, Tanner, Whitehouse and coworkers developed an alternative bone age measurement system (Thodberg et al., 2012). Their method analyses shape and the tendency of ossification centres to change during maturation rather than their size (Waldt et al., 2014). They first released standards for skeletal maturation in 1959 and in 1962 their first skeletal maturity assessment method followed (J. M. Tanner & Whitehouse, 1959, 1962). The Tanner-Whithouse 1 (TW1) method was based on the data of 2600 radiographs obtained in the 1950s and 1960s of British children of average socio-economic class (J. M. Tanner & Whitehouse, 1962). In this method 20 bones of the hand and wrist (13 long bones: radius; ulna; metacarpals 1, 3, and 5; proximal, middle, and distal phalanges 1, 3, and 5; and seven round bones: the carpals excluding the pisiform) are described and used as maturity indicators (Malina & Beunen, 2002). A maturity stage from A to I is assigned to each bone and subsequently a score is attached to each stage, which is different for males and females. The scores are then summed up and a summed maturity score (SMS) is produced. This summed score is then translated into a bone age by comparing it to a table with data derived from a selected population (Cameron, 1984; Thodberg et al., 2012; Waldt et al., 2014). Tanner and Whitehouse monitored their system critically and therefore modified their method in 1975 thus resulting in the Tanner-Whitehouse 2 (TW2) method (Cameron, 2004a; J. M. Tanner et al., 1975; Thodberg et al., 2012). In the TW2 method they revised their scoring system to allow for the computation of three different scores (Cameron, 1984) yet the criteria for evaluation of the maturity status was not changed (Malina & Beunen, 2002).

In addition to the 20-bone scoring system, they added a system with 13 bones called RUS (see Figure 2) that uses the radius, ulna, and short bones (first, third and fifth digital rays) and a system called CARPALS that uses the seven carpal bones. However, the CARPALS scoring system is drastically less useful after subjects reach the age of 12 (Waldt et al., 2014). According to a study by King et al. the average time needed for a TW2 bone age assessment is 7.9 minutes (King et al., 1994).

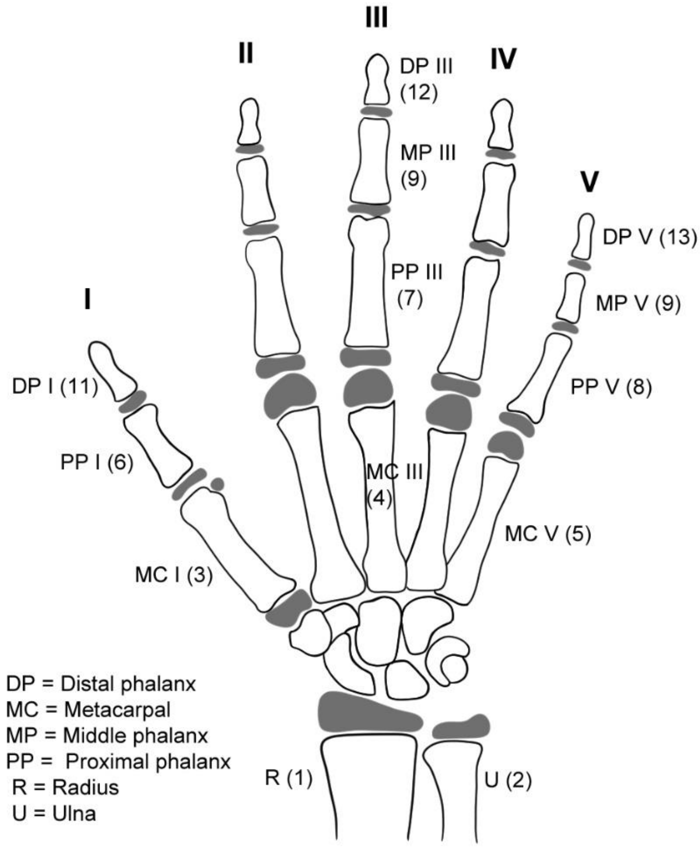

Figure 2: Epiphyseal centres scored in the RUS method. The scoring order is indicated by the numbers in parentheses. Adapted from (Waldt et al., 2014).

The third version of their bone age method, the Tanner-White 3 (TW3) method, was published in 2001 to further improve the accuracy and reproducibility (Cavallo et al., 2021; J. M. Tanner et al., 2001). In this version Tanner and colleagues incorporated secular trends that overall growth in size gets larger and that maturational timing is earlier with each subsequent generation (Cameron, 2004a). They modified their reference values and graphs by adding samples of British, Belgian, Italian, Spanish, Argentinean, American, and Japanese children and adolescents (Malina & Beunen, 2002) assessed in the 1970s, 1980s and 1990s (Cameron, 2004a). These changes led to the result that the TW3 method estimates a slightly younger bone age than the TW2 method (Ahmed & Warner, 2007). Furthermore, the TW3 method only contains the RUS and the CARPALS scoring system, as the 20-bone scoring system has been abolished. The mixture of the RUS and the carpal maturity score was found to be of no major value (Cameron, 2004a). For clinical routines, only the RUS score is acceptable (Waldt et al., 2014).

Compared to the GP method, the TW method is said to be more objective with a smaller intra-rater variation and a higher reproducibility (Bull et al., 1999; Prokop-Piotrkowska et al., 2021). Another drawback is that, in contrast to the TW method, there is only one version since 1959 and it is not applicable to every type of population (Prokop-Piotrkowska et al., 2021). However, the TW method has a longer assessment time (King et al., 1994).

1.3.6 Fels method

The third generation of bone age methods is called the Fels method and was first published in 1988 (Roche et al., 1988). It is based on the Fels Longitudinal Growth Study, which was eponymous for the method. In this study 13823 serial radiographs of the left hand and wrist of 355 boys and 322 girls born between 1928 and 1974 were obtained. These recordings range from the first month of a child's life up to the age of 22 years (J. M. Tanner, 1989). Through these radiographs, 130 maturity indicators were discovered, however only 98 were selected as indicators (Cameron, 2004a). These maturity indicators represent radiographic features occurring during the maturation process of every child and are further analysed with a computerized system. The output of this programme is the estimated bone age and a mean error (Chumela et al., 1989). Nevertheless, the Fels method is the most laborious bone age assessment method and has not gained broad recognition as of now (Prokop-Piotrkowska et al., 2021; Thodberg et al., 2012).

Due to the fact that manual methods tend to be more time consuming or have high inter- and intra-rater variability, the need for an objective new method arose (Prokop-Piotrkowska et al., 2021). Tanner recognised early that the task of bone age assessment is well suited for computerized systems (J. M. Tanner, 1989). He was one of the first to introduce a computerized system called the Computer-Assisted Skeletal Age Score (CASAS) (J. M. Tanner & Gibbons, 1994). According to Tanner et al. (1994) and Frisch et al. (1996), this system is more reliable than manual methods, but is limited by the duration of bone age estimation since it can take even longer (Satoh, 2015). More than 15 other computerized methods have been developed, but due to their limited automation and missing standardization, did not become widespread in clinical practice (Cavallo et al., 2021; Thodberg, Kreiborg, et al., 2009). Only the use of advanced mathematical methods and increasing performance of computers made the development of automated assessment of bone age possible,using the BoneXpert (BX) method (Thodberg et al., 2012).

1.3.7 BoneXpert method

BoneXpert was created by the Visiana company in Hørsholm, Denmark and was first released in 2009 (Thodberg, Kreiborg, et al., 2009). The processing of radiographic images is divided into three layers (see figure 3) (Visiana, 2019). In version 1 and 2 of the BoneXpert method 13 RUS bones (the same bones as in the TW2 and TW3 method) were analysed. Version 3 uses 21 bones (5 metacarpals, 14 phalanges, radius and ulna) for analysis, to better concur with manual ratings (Prokop-Piotrkowska et al., 2021; Visiana, 2021b). However, the carpal bones are not used for calculations of bone age of boys older than 12 and girls older than 10 years, since there is little carpal development above this age (Visiana, 2019).

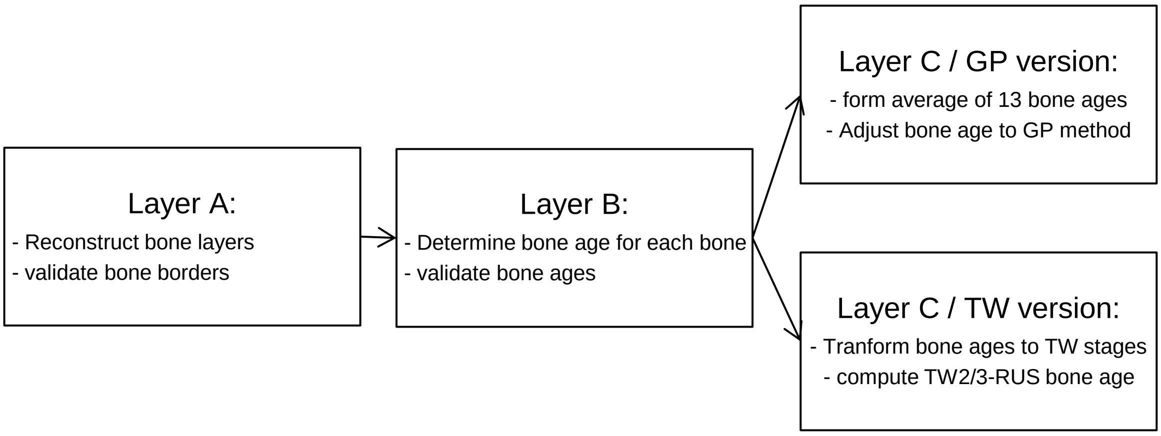

Figure 3: Architecture of BoneXpert using 13 bones for analysis. The architecture is the same in version 3 when using 21 bones. Adapted from (Thodberg, Kreiborg, et al., 2009; Visiana, 2019).

In Layer A, the borders of bones are reconstructed by using a sophisticated algorithm developed in part by machine learning. Through supervised and unsupervised machine learning, the algorithm is able to locate certain landmarks on the bones and allowed bone shapes. The bone borders are validated through this process and rejected if they do not match a specific model (Visiana, 2019), or the image is rejected, if there are less than eight bones that were approved (Thodberg et al., 2022).The bone age algorithm is made ab initio and does not learn further when running in a hospital or other institutions (Visiana, 2019). In Layer B, an intrinsic bone age value for each bone is calculated from features that describe the texture of fusion in the growth plate, from intensities and from bone shape scores and bone density scores (Satoh, 2015; Thodberg, Kreiborg, et al., 2009). Layer C then transforms this data into the intrinsic bone age values, either according to the TW, or the GP bone age criteria. Additional to bone age assessment, BoneXpert can calculate a bone health index as well. For the bone health index, cortical thickness of the second, third and fourth metacarpal shaft is measured and then matched to a healthy population of the same sex and bone age (Thodberg et al., 2022).

Data used to develop layers A and B are from heathy Danish children and from Danish and Belgian children from a clinical setting. The BoneXpert method was originally validated with images from the Greulich Pyle atlas, the RH validation study, and a longitudinal precision study (Thodberg, Kreiborg, et al., 2009). Several additional studies verified the reliability and precision of the BoneXpert method in various populations and the validity for identifying and diagnosing children suffering from a range of disorders. However, most of these studies were published by at least one person connected in some way to the Visiana company (Prokop-Piotrkowska et al., 2021). Since the release of BoneXpert, new automated systems based on artificial intelligence and deep learning technologies, using convolutional neural networks were developed and published, with some of them already in use (16BIT, 2022; Lee et al., 2017; Liu et al., 2019; Spampinato et al., 2017; Van Steenkiste et al., 2018).

1.3.8 other methods

In addition to the assessment with radiographs, other imaging modalities for bone age determination like ultrasound and magnetic resonance (MR) are available. Ultrasound assessment involves measuring the ossifying cartilage structures within the wrist by transmitting an ultrasonic wave through the distal radius and ulnar epiphysis of the individual. Though this method has the advantage of not exposing subjects to radiation, it still needs improvements regarding reproducibility (Cavallo et al., 2021; Prokop-Piotrkowska et al., 2021; Satoh, 2015). For MR assessments, an open compact MR imager with a permanent magnet was developed as a paediatric hand scanner for bone age evaluation. Studies showed a strong positive correlation between bone age and chronological age and confirmed the method as reliable and valid, with a high intra- and inter-rater reproducibility (Terada et al., 2013, 2014). Though larger-scaled studies are necessary for validation. The major drawback of this non-invasive method is its long recording time of 2 min and 44 sec. Since the subject needs to hold still for this time, it might not be suitable for young children (Prokop-Piotrkowska et al., 2021). Several comparisons of the various bone age methods mentioned were made and some of the disadvantages and advantages, as well as the radiation risks, are listed in table 1.

Table 1: Comparison of the disadvantages, advantages and radiation risk of the different bone age methods (Cavallo et al., 2021; Prokop-Piotrkowska et al., 2021; Satoh, 2015).

	Method	**Disadvantages**	**Advantages**
GP	Atlas method	- high intra- and inter-rater variability - one version since 1959	- widely recognised - quick - easy to learn
TW	Scoring method	- Time consuming - subjective evaluation	- more reliable than GP - newest version of manual methods available (2001)
Fels	Scoring method	- limited experience	- standardized evaluation of errors
BX	Automated computerized calculation	- automated, but radiologist not fully eliminated - does not learn	- accuracy - precision - validated for various populations
Ultrasound	Sound velocity measurement	- time consuming - operator-dependent - difficulty of standardization	- no radiation - low cost
MR	Scoring method	- time consuming - not easily accessible - no movements during recording	- no radiation

1.4 Adult height prediction

Combined with anthropometric data, bone age can deliver estimated predictions of adult height (Lolli et al., 2021). This is important for talent identification and development since growth and maturation greatly influence the physical performance of young athletes (Beunen & Malina, 2007). A positive correlation between an athlete's height and their athletic performance has been postulated in several reports (Malina, Eisenmann, et al., 2004; Philippaerts et al., 2006). Therefore, predictions of the adult height can be important for later success in certain sports and thus a valuable extension of the maturity assessment via bone age (Ostojic, 2013). Most of the commonly used adult height prediction methods are based on bone age methods. Table 2 gives an overview on which bone age method they are based on.

Table 2: The four generations of the most used adult height prediction methods based on bone age (including the bone age methods they use). Adapted from (Thodberg et al., 2012)

Bone age generation		Bone age method	Adult height prediction method	Bone age used in adult height prediction
1	1946-59	Todd/Greulich-Pyle (GP)	Bayley-Pinneau (1946/52)	Todd/GP
			Roche-Wainer-Thissen (RWT) (1975)	GP bone-specific
2	1962-83	Tanner-Whitehouse (TW) – TW1, TW2, TW3	TW Mark I (1975)	TW2
			TW Mark II (1983)	TW2
			TW3 (2001)	Summed maturity score (SMS)
3	1987-93	Fels	RWT/Khamis (1993)	Fels
4	2008-2019	BoneXpert versions 1-3	BoneXpert (2009)	BoneXpert version 2
			BoneXpert version 2 (2013)	BoneXpert version 2
			BoneXpert version 3 (2019)	BoneXpert version 3

All adult height prediction models listed in table 2 have in common that they use the parameters current height (h), bone age, age, and sex for predictions of adult height (H). They differ however in the type of bone age they use and therefore the weight assigned to the bones of the hand and wrist, as well as reliability. Furthermore, methods vary in validity, in the population the models are based on, and mathematical models used.

1.4.1 Bayley-Pinneau method

Bayley first published tables for height prediction in 1946 and in 1952, modifying and republishing them with Pinneau (Cameron, 2004b). Predictions of adult height are based on correlation between skeletal age from bone age methods and proportions of subjects' adult statures at the time the radiographs were recorded (Bayley & Pinneau, 1952). To calculate adult height, the stature at the time of the radiographic recording is divided by the growth fraction determined in accordance with bone age (Costa et al., 2017). Bone age tables providing the subject's predicted percentage of adult height were originally based on Todd's atlas and revised and modified in 1952, due to the publication of the Atlas of Skeletal Maturation by Greulich and Pyle in 1950, whose tables contain different values for boys and girls. The revision additionally included separate tables for accelerated or delayed bone age (Cameron, 2004b). Bone age is accelerated if it is more than one year ahead of the chronological age and delayed if it is more than one year behind (Topor et al., 2010).

1.4.2 Tanner-Whitehouse methods

Same as with the Tanner-Whitehouse bone age methods, there are three different versions of height prediction methods. The first one, called TW Mark I, was published in 1975 and is based on bone age method TW2, using the RUS scoring system. Additionally, standard anthropometric measurements were made. Tanner and colleagues then applied classical regression analysis to the obtained data. To get the best results for adult height prediction, various combinations of predictor variables were regressed. The Mark I version delivered the best results including chronological age, RUS bone age and present height (Cameron, 2004b). However, before the ages of 7 in girls and 10 in boys, the RUS bone age is not required (Malina & Beunen, 2002). Furthermore, the prediction equation significantly improves with knowledge on whether a female subject is pre- or post-menarchael. Partial regression coefficients were smoothed graphically (Cameron, 2004b).

Need for a revision of the TW Mark I arose since its data is based on recordings and measurements of healthy children, while the method was also applied to children with suspected growth abnormalities (Cameron, 2004b). Therefore, Tanner and colleagues included in their TW Mark II method source samples of very short and very tall children (J. M. Tanner et al., 1983). Additionally, the original predictor variables were adapted, and the longitudinal variables increment of height (ΔH) and increment of RUS bone age (ΔRUS) included. However, the Mark II version provides separate equations if these data are not available. For girls, like in the TW Mark I, separate sets of equations for pre- or post-menarchael subjects are available (Cameron, 1984, 2004b). The RUS bone age was included from the age of 8 years for boys and 6 years for girls.

The third height prediction equation by Tanner et al. is called TW3 and was released in 2001 (J. M. Tanner et al., 2001). Instead of bone age, a bone maturity score is used as a predictor variable to address the effect of environmental factors like nutrition, socioeconomic status and health caused by secular trends, since it represents actual maturity more accurately (Cameron, 2004b; Lolli et al., 2021). The equations are represented in the form of the following formula: final height = current height + a x RUS-score + b. The constants a and b vary according to the chronological age of the subject (Costa et al., 2017). Height increments are used between the age of 11 to 13.9 in girls and 12 to 14.9 in boys. Predictions can again be improved by knowledge of the pre- or post-menarchael status (Cameron, 2004b).

1.4.3 Roche-Wainer-Thissen method

The Roche-Wainer-Thissen (RWT) method was published in the same year as the TW Mark I and uses a similar mathematical framework. It is considered one of the most accurate methods to predict adult heights of healthy children. The RWT model is based on linear regression and includes the variables age, current stature, current weight, average stature of the parents and bone age assessed by the Greulich-Pyle method (Khamis & Roche, 1994; Olivares et al., 2020; Thodberg et al., 2012).

The RWT method was modified in 1993 by Khamis and Roche for simplification. Therefore, they excluded the bone age in the Khamis-Roche method. It is however based on the data of the Fels Longitudinal Study and directly calculates adult height from a linear combination of the variables: Current height, body mass, chronological age, and average stature of the biological parents. It can be used for children from the age of 4 to 17.5 (Olivares et al., 2020; Topor et al., 2010).

1.4.4 BoneXpert methods

Like Tanner, Whitehouse, and colleagues, Thodberg et al. not only published a bone age model but also a new adult height prediction method. The first version was published in 2009, the third version in 2019 (Thodberg et al., 2012; Visiana, 2021b). The BoneXpert adult height prediction model is based on the Bayley & Pinneaus method, where predicted adult height, here called H_{raw}, is estimated from bone age, chronological age, height and sex (Satoh, 2015). In the Bayley-Pinneau-model, growth potential, which is the remaining growth divided by adult height, has a linear dependency on bone and chronological age (Visiana, 2021a). In the BoneXpert model however, growth potential was constructed as a non-linear function of two variables implemented as a neural network (Thodberg, Jenni, et al., 2009). This Bayley-Pinneau type prediction of H_{raw} is called a relative height model, as it makes predictions relative to the current height. The final adult height prediction is obtained by combining the predictions of this relative model with one from an absolute model using a weighted average depending on the bone age (see figure 4).

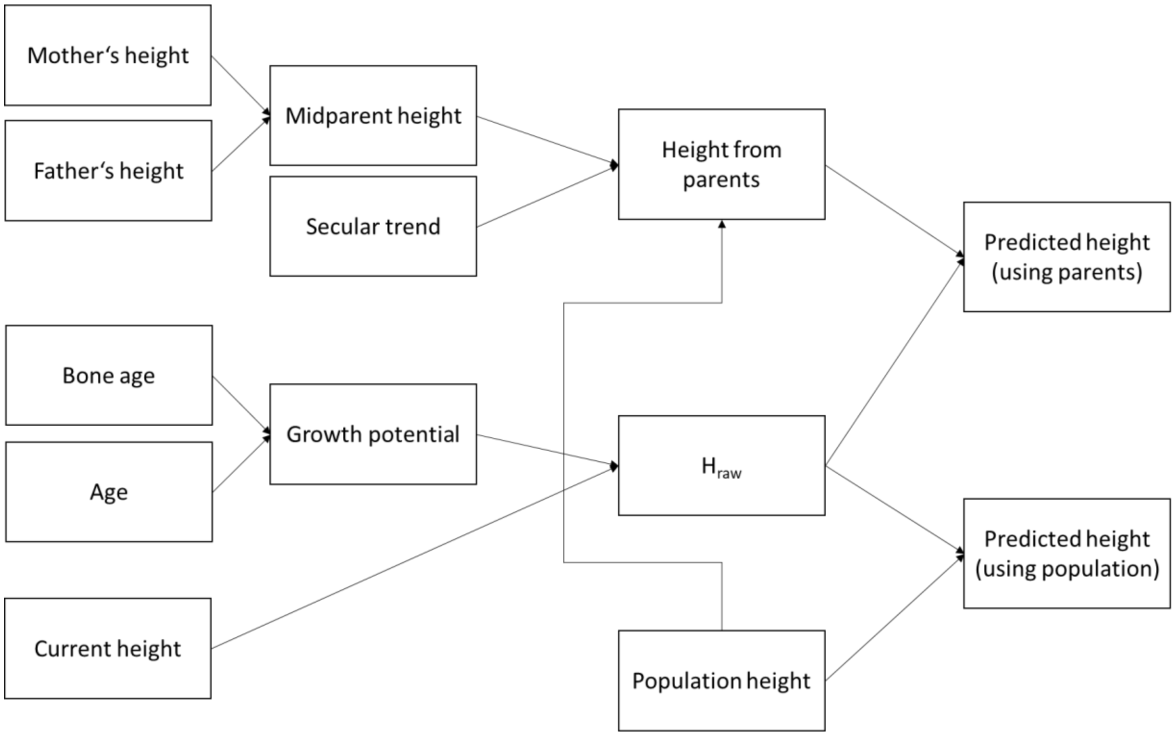

Figure 4: Flow chart of the BoneXpert height prediction model. Adapted from (Thodberg, Jenni, et al., 2009)

In the absolute model, predictions are made in absolute terms either based on the parents' heights or the population standard height. Optionally, the height a menarche and the BMI can be added as additional modules (Thodberg, Jenni, et al., 2009). The BoneXpert adult height prediction model was developed with the intent to use the bone age determined by BoneXpert. However, it can be used with manually assessed GP bone age, but, as a consequence, will lead to larger uncertainties in predictions (Visiana, 2021a).

The first version of the BoneXpert height prediction model is based on the First Zurich Longitudinal Study and validated using the Third Zurich Longitudinal Study (Thodberg, Jenni, et al., 2009). Since then, additional models for other ethnicities were added. However, there have been no height studies yet that are suitable with bone age on African Americans and Indians, therefore limiting reliability (Visiana, 2021a).

As anthropometric measurements like height (Madden et al., 2020) and bone age vary between populations (Ostojic, 2013), ethnic variation should be considered (Malina et al., 2015). Additionally, height and bone age can be impacted by several other factors including, nutrition, genetic, metabolic and social factors, and acute or chronic diseases, including endocrine dysfunctions (Cavallo et al., 2021). Therefore, in order to correctly use and interpret the results of bone age and height prediction methods, it is important to know which factors can affect growth and adult height.

1.5 Influences on growth and adult height

Growth appears to occur in short bursts of growth activity, called saltation, suspended by periods of no growth. The postnatal growth curve can be divided into five distinct phases. It starts with a phase of rapid growth during infancy, followed by a steady growth in childhood. After this comes a short period of rapid growth in the juvenile period and a second phase of rapid growth during adolescence followed by very slow growth approaching adulthood. The juvenile growth spurt occurs at a similar age in boys and girls but may vary in magnitude. However, the adolescent growth spurt differs greatly between the sexes. Girls enter this phase almost two years earlier than boys with a slightly smaller gain of height (Cameron, 2022a).

The process of growth is complex and controlled by constantly interacting genetic, epigenetic, and environmental factors (Cameron, 2022a). Every child possesses a predetermined genetic growth potential. This potential can be altered by pre- and postnatal influences and optimal growth can only be achieved, if all contributing factors operate in harmony (Mousikou et al., 2023). Since growth remains plastic into adolescence, every development phase is susceptible to these alterations (Thompson, 2022).

The foetal growth is mostly affected by maternal, genetic, foetal, and placental factors (Norris, 2022). The main factor influencing growth during infancy is nutrition (Mousikou et al., 2023), whereas during childhood the main influence is thought to be hormonal regulation (Benyi & Sävendahl, 2017). During adolescence, the pubertal growth spurt occurs (Roelants & Cameron, 2022) regulated by hormonal changes, especially changes in the sex hormones (Mousikou et al., 2023).

The Alteration of genetic growth potential by environmental influences depends on timing, strength, frequency, duration, and sex. These influences will primarily affect the endocrine system (Cameron, 2022a). These endocrine factors are in general essential for normal human growth (Christian & Smith, 2018).

1.5.1 Endocrine control

Growth hormone (GH), insulin-like growth factor 1 (IGF-1), thyroid hormones and sex hormones are all regulators of growth at varying ages. During the first year of a child's life, growth is mostly dependent on nutrition and thyroid hormone regulation. However, at the end of this first year, the main regulation of endocrine-related growth is mediated by the GH-IGF-1 axis. The GH-IGF-1 axis stays the main regulator until the beginning of puberty, when GH productions increases due to rising levels of testosterone and oestrogen. After the closing of the growth plates, the production of GH and IGF-1 is reduced but stays active at a lower level through life (Miller, 2022).

GH is the main hormone in linear growth. It is secreted by the pituitary gland and regulated by both the growth hormone releasing hormone (GHRH) and the inhibitory hormone somatostatin (Benyi & Sävendahl, 2017; Miller, 2022). Furthermore, stimulation occurs by ghrelin and inhibition by a negative control feedback with IGF-1 (Meinhardt & Ho, 2006). The pulsatile secretion of GH is spread throughout the day, but is increased during sleep and can be influenced by several environmental factors like blood glucose levels, exercise, stress and available amino acids (Miller, 2022; Thompson, 2022).

GH regulates the production of IGF-1. It is produced mainly in the liver, but can also be produced by other tissues, such as in the growth plate (Benyi & Sävendahl, 2017; Savage, 2013). Furthermore, GH affects growth both directly – at the growth plate by stimulating the chondrogenesis – and indirectly via IGF-1 (Benyi & Sävendahl, 2017; Mousikou et al., 2023). At the growth plate, IGF-1 is responsible for the stimulation of hypertrophy and proliferation of chondrocytes and by affecting osteoblasts for ossification (Benyi & Sävendahl, 2017). However, growth is also influenced by other hormones like insulin, thyroid hormones, leptin and sex steroids (see table 3) (Benyi & Sävendahl, 2017).

Table 3: Overview of the main hormones and growth factors regulating human growth. Adapted from (Benyi & Sävendahl, 2017)

Type of hormone /growth factor	**Main effects on growth**
GH	Stimulates the production of IGF-1 in the liver; Stimulates chondrogenesis in the growth plate (Mousikou et al., 2023; Benyi & Sävendahl, 2017)
IGF-1	stimulates hypertrophy and proliferation of chondrocytes and affects osteoblasts for ossification; stimulates uptake of amino acids (Benyi & Sävendahl, 2017).
Insulin	binds to the IGF-1 receptor to increases the growth velocity; increases the amount of free IGF-1 in the circulation (Zhang et al., 2014)
Thyroid hormones	thyroid hormone receptors in the growth plate regulate bone mineral density and bone turnover; promotion of hypertrophic chondrocyte differentiation and cell volume expansion; stimulation of clonal expansion of chondrocyte progenitor cells and inhibition of subsequent cell proliferation (Bassett & Williams, 2016)
Leptin	stimulates GH secretion on the hypothalamic level (Tannenbaum et al., 1998); stimulates the proliferation of chondrocytes and the differentiation of cells in growth plate (Maor et al., 2002).
Sex steroids	Stimulate secretion of GH (Meinhardt & Ho, 2006; Perry et al., 2008).; oestrogen leads to epiphyseal closure in late puberty (Misra, 2008)

GH = growth hormone, IGF-1 = insulin-like growth factor 1

Insulin plays an important role in foetal and childhood growth. By binding to the IGF-1 receptor it increases the growth velocity. Furthermore, it increases the amount of free IGF-1 in the circulation (Zhang et al., 2014).

The thyroid hormones are important throughout growth. Receptors of thyroid hormones are found in the growth plate and regulate bone mineral density and bone turnover. Furthermore, they promote hypertrophic chondrocyte differentiation and cell volume expansion and stimulate the clonal expansion of chondrocyte progenitor cells and the inhibition of the following cell proliferation (Bassett & Williams, 2016).

Children with congenital hypothyroidism show a delay in bone age and tend to be of shorter stature. By contrast, hyperthyroidism advances bone maturation and accelerates growth. This leads to an early closing of the growth plates and therefore decreased adult height (Thompson, 2022). There are several other endocrine disorders that might induce growth impairment. The majority of these disorders should be noticeable at school entry but some may only be recognized as late as puberty (Miller, 2022).

Another hormone regulating growth is leptin. It is mainly produced by white adipose cells but also by other tissues including the pituitary gland, placenta, and skeletal muscle (Benyi & Sävendahl, 2017). Leptin has two ways to influence growth: First, it is able to stimulate GH secretion on the hypothalamic level (Tannenbaum et al., 1998). Second, it has a local effect in the growth plate. Here, it stimulates the proliferation of chondrocytes and the differentiation of cells (Maor et al., 2002).

During puberty, growth is strongly influenced by sex hormones including oestrogen and testosterone. The gonads are mainly responsible for producing these hormones. Oestrogen is important for growth for boys and girls. In girls, the main production of oestrogen is carried out by the ovaries. In boys, it is mainly produced in peripheral tissues by aromatizing androgens and smaller amounts in the testes. Furthermore, it is synthesised locally in the growth plate (Benyi & Sävendahl, 2017).

A characteristic feature of puberty is the activation of the hypothalamic-pituitary-gonadal axes (Benyi & Sävendahl, 2017). Through secretion of the gonadotropin releasing hormone (GnRH) the release of luteinising hormone/follicle stimulating hormone (LH/FSH) is stimulated from the pituitary gland. LH/FSH then stimulates the production of sex steroids respectively in the ovaries and testes (Christian & Smith, 2018; Styne, 2003). Testosterone stimulates GH secretion through a conversion to oestrogen by aromatization (Perry et al., 2008). Oestrogens effect on growth stems from regulating the secretion of GH by reducing the IGF-1 negative feedback loop (Meinhardt & Ho, 2006). GH and oestradiol show an influence on growth in boys and girls during puberty (Delemarre-van de Waal et al., 2001) and is in both sexes responsible for the initiation of the pubertal growth spurt (Perry et al., 2008). In late puberty however, increased oestrogen levels finally lead to epiphyseal closure in boys and girls (Börjesson et al., 2012; Misra, 2008).

1.5.2 Genetic influence

Height is a highly heritable trait (Czerwinski & Choh, 2022). Therefore, variations in height are greatly determined by genetic factors, but also by environmental factors (Jelenkovic et al., 2016). The heritability will be reduced due to higher environmental variation (Czerwinski & Choh, 2022). The genetic variations, if the environmental factors are shared, are greatest during early childhood. They remain present through childhood until early adulthood. However, the genetic contribution of height was greatest in adolescence with boys showing an even greater contribution (0.83) than girls (0.76) (Jelenkovic et al., 2016). These contributions vary in different populations. In populations where people have a greater risk of infectious diseases and undernutrition, environmental factors have a bigger impact on growth. Additionally, if countries are experiencing rapid economic growth, the environment and therefore the height of children changes drastically compared to their parents' height. This leads to a temporary decrease in heritability (Czerwinski & Choh, 2022).

1.5.3 Socio-economic effects on growth

The most significant contributions in human height variations are two environmental factors, namely quality of nutrition and morbidity on the population level. They represent the wellbeing of society. These factors indicate a populations' degree of social inequality and inform about economic condition changes (Kozieł, 2022). In most European countries, the populations' height increased since the mid-19th century (McCrory et al., 2017) due to improved hygiene, health, socioeconomic equality, increasing gross domestic product, and socioeconomic development. The most important factor seems to be the education level of the mother (Kozieł, 2022). Other contributing factors are housing, income, health care and sanitation (Cameron, 2022c).

Social factors do not affect height directly, but rather through environmental factors. These environmental factors include morbidity, nutrition, physical workload, harmful habits like smoking, alcohol consumption and hygienic behaviour, level of pollutants, and psychosocial stress (Kozieł, 2022). For example, due to poor economic status a family might not be able to provide adequate nutrition or a home that meets basic health requirements (Perez-Escamilla et al., 2018). These poor housing conditions in return might make children more susceptible to infectious diseases (Sari et al., 2021).

1.5.4 Environmental factors

Other than the influence of socio-economic factors and nutrition on growth, other environmental factors can alter growth as well. These factors include altitude, climate, and temperature. The mechanisms of temperature and climate affecting growth, however, are not well understood as of yet. Additionally, pollutants like lead, some organic compounds and components of air pollution can have an adverse effect on growth. The size of the effect is dependent on the extent of the exposure (Schell & Rousham, 2022). Chronic exposure to pathogens and frequent infections may affect growth as well due to inflammation (Thompson, 2022).

1.5.5 Nutrition

If one rules out growth disorders or infections preventing a child to achieve normal height, growth rates and height can be used as an indicator for the adequacy of the nutritional status of a child. Globally, variations in average height are greatly influenced by differences in nutrition (Cameron, 2022c). The adequate amount of nutrients depend on age, sex, health status, activity level, rate of growth and physical environment (N. Boisseau, 2006; Cameron, 2022c). The main function of essential macronutrients is to deliver energy, especially through the carbohydrates, and to promote growth and repair mechanisms, utilizing primarily proteins and fats. Essential micronutrients like minerals and vitamins are important for normal growth as well (Cameron, 2022c). At the age of 1 year, growth accounts for about 3% of the total energy requirements, during adolescence for about 4%. These demands are higher for boys than for girls (Christian & Smith, 2018).

Infancy is a time of high growth velocities and is highly dependent on adequate amounts of nutrition (Cameron, 2022c; Norris, 2022). Therefore, the body is sensitive to perturbations or stress (Cameron, 2022c). If these nutritional amounts are not met, malnutrition can lead to interferences in growth like stunting (Norris, 2022; Sari et al., 2021). This suppression of growth might be the body’s way to conserve energy for essential mechanisms (Christian & Smith, 2018). The retardation in linear growth can be irreversible without intervention. Even with interventions, catch-up growth might not always be completely possible. Catch-up growth refers to children gaining height faster than the expected linear growth velocity for their sex and age (Leroy et al., 2020). However, stunting and catch-up growth is still possible through childhood and adolescence (Thompson, 2022) since in puberty, about 15-25% of the adult height can still be attained (Christian & Smith, 2018).

Growth is probably impacted by malnutrition during childhood due to several disturbances of the GH-IGF-1 axis. This may include reduced plasma levels of insulin, IGF-1, leptin, and thyroid hormones and increased levels of IGF-binding protein, GH levels and glucocorticoids (Savage, 2013; Thompson, 2022). The reduced IGF-1 and the high GH levels combined indicate a GH resistance (Savage, 2013). The secretion of IGF-1 may be directly regulated by amino acids and is therefore sensitive to alterations in the nitrogen balance (Thompson, 2022). Severe malnutrition of proteins, lack of zinc and certain vitamins probably lead to reduced IGF-1 levels (Sari et al., 2021; Thompson, 2022). In Europe, malnutrition caused by poor diet is rare nowadays, but is still a possibility for children living in poverty or abusive environments (National Health Service - UK, 2023). However, the estimated prevalence of restrictive eating disorders like anorexia nervosa in children and adolescent is increasing (A. B. Tanner, 2023).

Growth periods during childhood and especially puberty present a nutritional vulnerability since the final adult height can still be negatively impacted (Barker, 2021; A. B. Tanner, 2023). Studies show that patients with anorexia nervosa have a significantly lower final adult height than expected (Misra, 2008; Modan-Moses et al., 2003, 2021; Swenne, 2013). However, if adult height is affected or catch-up growth is possible, depending on the time of onset, duration and severity of the illness, sex, and the remaining growth potential (Downey et al., 2023; Misra, 2008). The negative effect of insufficient energy on growth is greater when it occurs during phases of rapid growth, like the pubertal growth spurt, or when the effect persists over a longer period of time (A. B. Tanner, 2023).

The pubertal growth spurt is strongly influenced by sex hormones and by an increase in GH and IGF-1 secretion (Benyi & Sävendahl, 2017; Misra, 2008). Anorexia nervosa is associated with very low levels of IGF-1 and a GH resistance as seen in severe malnutrition (Misra, 2008; Thompson, 2022). Furthermore, hypogonadotropic hypogonadism, hypercortisolemia and altered secretion of adipokines and appetite regulating hormones has been reported in individuals with anorexia nervosa (Misra & Klibanski, 2016).

Because of the different ages at which the pubertal growth spurt occurs in boys and girls, sex specific differences in the loss of genetic height potential and catch-up growth occur (Downey et al., 2023). Girls with anorexia nervosa showed more severe impairments in growth, if they presented the disorder at the age of 13 years or younger or if they were less than 1 year after menarche compared to older girls. These girls might have already gone through their growth spurt with enough energy for normal growth at the onset of anorexia nervosa (Modan-Moses et al., 2012). Therefore, diagnosis comes with a greater risk of growth stunting in younger girls (Downey et al., 2023).

In a study concerning boys with anorexia nervosa, catch-up growth was possible during the first year for boys who had not yet started their growth spurt. Boys, who had already initiated their growth spurt were not able to completely catch-up to the predicted adult height. The loss in height equated to about 4.5 cm of potential height (Downey et al., 2023; Swenne, 2013).

The mean age of diagnosis of anorexia nervosa is 12.2 years (Morris et al., 2022; van Eeden et al., 2021). Girls with normal growth attain peak height velocity generally at the age of 12 and boys with normal growth at the age of 14 (Soliman et al., 2014). This means that at the onset of disorder, boys still have a more significant growth potential left. Therefore, boys with anorexia nervosa are more probable to have a reduced adult height than girls (Misra, 2008).

1.5.6 Stress

Stress is defined as the reaction of the human body to a threat or a perceived threat (Mousikou et al., 2023; Schell & Rousham, 2022). A stressor can either be psychological/emotional or it can be physical. Psychological or emotional stressors include anxiety, frustration, or fear. Physical stressors include, extreme heat or cold, disruptions of the internal environment such as anorexia nervosa and hypoglycaemia, or multifaceted stressors like injury or exercise (Mousikou et al., 2023). The body's stress response (see figure 5) is to activate the adaptive central nervous system and peripheral nervous system (Charmandari et al., 2003; Chrousos & Gold, 1992) including the hypothalamic-pituitary-adrenal (HPA) axis to restore homeostasis. The vulnerability to stressors is increased from prenatal life through adolescence, due to plasticity during this period. Growth, metabolism, and immune responses can be negatively affected if stress is high in magnitude or in duration (Charmandari et al., 2003) since energy is redirected to vital survival processes and stress response (Chrousos & Gold, 1992).

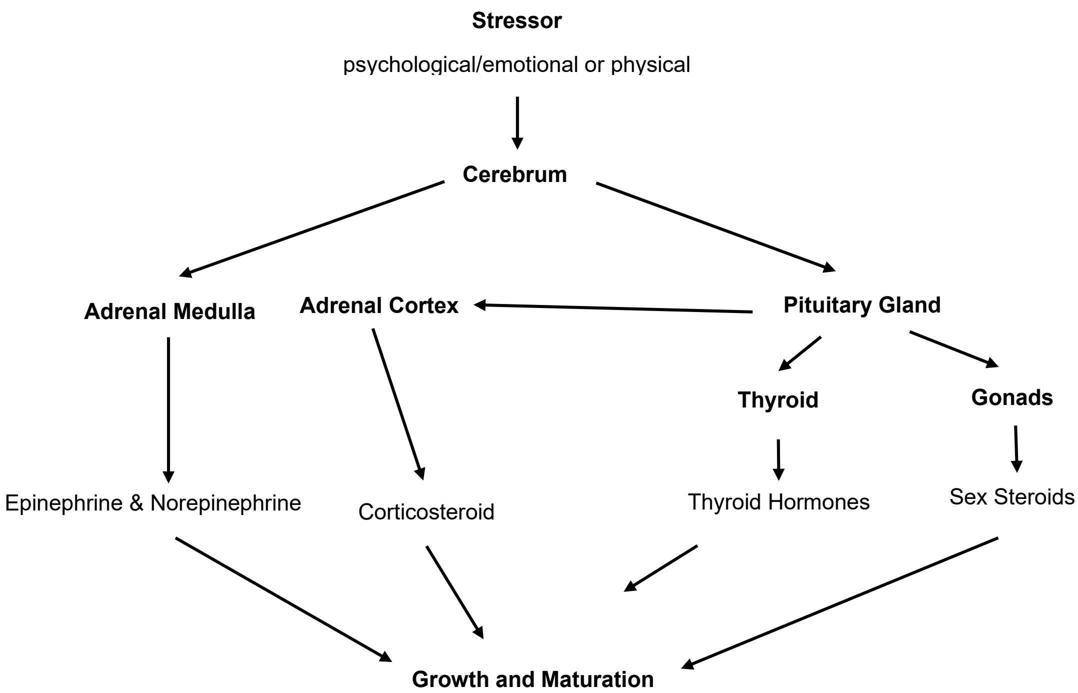

Figure 5: Schematic diagram of the biological response to stress. Adapted from (Schell & Rousham, 2022).

The acute response to stress is to activate the HPA axis and the sympathetic nervous system with increased release of epinephrine and norepinephrine. This response is designed to be time limited and it's antigrowth, catabolic, anti-reproductive, and immunosuppressive effects show no lasting consequences (Mousikou et al., 2023). However, if stress persists, the stress response system is chronically activated and might lead to a maladaptive response due to an increased production of glucocorticoids and corticotropin-releasing hormone (CRH) (Charmandari et al., 2003). These maladaptive responses inhibit the GH-IGF-1, the gonadal, and the thyroid axis and increase cortisol levels. Hypercortisolism especially shows adverse effects in growth. During puberty, growth is affected through the suppression of GH and the inhibition of gonadotrophins (Mousikou et al., 2023). This inhibition of gonadal secretion has been shown in elite athletes (Cano Sokoloff et al., 2016), adolescent with anorexia nervosa (Schorr & Miller, 2017) and during longer time periods of negative energy balance (Rivier & Rivest, 1991). Other possible chronic stressors affecting growth include prenatal stress like alcohol use or maternal psychological stress, malnutrition, abusive environments, reactive attachment disorder of infancy, prolonged hospitalisation, emotional deprivation, inhibited child syndrome, wars, immigration, chronic illnesses like cancer, liver disease, cystic fibrosis, congenital heart disease, and chronic kidney disease, and intense exercise (Mousikou et al., 2023).

There has, however, also been concern, that extensive high intensity sports training like gymnastics, diving or figure skating might directly influence growth rates as well, but so far, no cross-sectional and longitudinal study supports this concern (Bergeron et al., 2015).

1.6 Height in Sport

Height is a highly heritable trait (Czerwinski & Choh, 2022) and variations in height are determined not only by genetic but also, to a lesser extent, by various environmental factors (Jelenkovic et al., 2016). In an important sporting event, a physical trait like height could give the necessary competitive edge because winning a gold or a silver medal may be decided by small margins (Simonton, 2017). In the process of talent identification, development, and selection, decisions need to be made about future adult abilities (Till & Baker, 2020). Since the correlation of an athlete's height and their athletic performance has been stated in several reports (Malina, Eisenmann, et al., 2004; Philippaerts et al., 2006), it is important to know the predicted adult height of an athlete because certain sports or positions within the sport might be better suited for certain athletes (Lloyd et al., 2014). However, to know which sports could be better suited, it is important to know the various advantages or disadvantages of taller or smaller human height in sports.

1.6.1 Advantages of short human height

Examples of advantages of shorter human height include the greater strength to weight ratio, higher power output, faster rotational acceleration, lower rotational inertia, greater acceleration of limbs, lower centre of gravity and therefore greater stability, changing directions of movements faster, lower air drag, and better heat dissipation (Samaras, 2007a, 2007c; Schell & Rousham, 2022; Sedeaud et al., 2014).

Muscles and bones of shorter athletes are stronger in proportion to the weight of their body, since the body weight has a higher increase than the cross-sectional area of muscles with increasing height. Therefore, athletes like climbers or gymnasts can more readily lift their own body (Samaras, 2007a) or weightlifters can more easily lift high weights on barbels. Short height and in correlation shorter limb length of weightlifters provides them with a mechanical advantage, since their smaller height reduces mechanical torque and vertical displacement distance of the barbel (Storey & Smith, 2012). Additionally, shorter people have a relatively higher power output compared to their weight. This gives smaller athletes another advantage in climbing (Samaras, 2007a).

The faster rotational acceleration, for example in rotations about the longitudinal axis of the body, is of benefit in sports like diving, gymnastics, and snowboard events like big air, slopestyle, and halfpipe. Other sports who might profit from the fast rotational capabilities are martial arts, dancing, and figure skating (Samaras, 2007a). Furthermore, it is easier for shorter athletes to start and end rotations than for taller athletes since they have lower rotational inertia. In addition, small martial arts athletes tend to be faster in their movements because of a the greater acceleration capabilities of their limbs. (Samaras, 2007c).

The higher strength to weight ratio, faster rotational capabilities and greater acceleration make smaller athletes better at change-of-direction (Samaras, 2007a). However, smaller people can not only change their direction more easily, but they are also at an advantage stopping their motion when running straight. Both would be good qualities for running backs or wide receivers (Samaras, 2007c; Šimonek, 2019). However, wide receivers also profit from greater reach that comes with greater height. Another asset for smaller running backs is the lower centre of gravity, it provides them with greater stability and is also advantageous in sports like wrestling, gymnastics, sailing, and surfing (Samaras, 2007a).

An athlete with a smaller and leaner stature will experience less air drag during running than a tall athlete (Sedeaud et al., 2014). A greater surface area relative to the size is furthermore advantageous since it can dissipate produced heat more efficiently. This is beneficial for short and lean athletes like marathon runners. An increase of height and weight leads to an increase of the surface area at a lower rate than generation of body heat (Samaras, 2007a; Schell & Rousham, 2022; Sedeaud et al., 2014).

1.6.2 Advantages of tall human height

Benefits of a taller height in sports are for example absolute strength, better visibility, greater reach, higher jumping height in total, greater stride length, higher centre of gravity, greater momentum, greater rotational impulse, greater maximum acceleration force, greater release height and less wave resistance (Kjendlie & Stallman, 2011; Masanovic et al., 2018; Samaras, 2007b, 2007c; Sedeaud et al., 2014). In many sports like javelin, discus, boxing, and American football, absolute strength gives athletes a competitive edge. Absolute strength correlates directly with the cross-sectional muscle area and increases with height. In combat sports like boxing, this advantage of taller height is one reason that led to the development of weight classes to even out the playing field (Samaras, 2007b).

Even though the correlation between limb length and body height varies in different populations (Mohanty et al., 2001), taller people tend to have a longer reach which is of benefit in sports like volleyball, basketball, boxing or tennis (Samaras, 2007b). In Basketball, a greater reach gets players closer to the basket or gives them an advantage during defensive tasks. Volleyball players profit from a tall height in defensive and offensive actions, especially in actions at or over the top of the net (Masanovic et al., 2018). Another benefit of longer limbs is a greater stride length, which is especially favourable in the 400m track event (Sedeaud et al., 2014).

As a quarterback, it can be advantageous to be tall in order to see over the heads of the defensive and offensive line while passing to teammates (Samaras, 2007b). Another benefit for tall players in American football is that they have a greater momentum which makes it harder to stop them (Samaras, 2007c).

The vertical jumping height measured from the ground is not dependent on the height of the athlete. Taller athletes do however have a higher jumping reach which is beneficial for wide receivers, volleyball or basketball players (Masanovic et al., 2018; Samaras, 2007b). Additionally, they have a higher centre of gravity which is advantageous in events like high jump or pole vault (Samaras, 2007b).

Tall athletes also have a competitive edge in track and field events like javelin, hammer throw, and discus throw. In discus and hammer throw events, tall athletes profit from a greater rotational impulse, a more favourable relation of throwing weight to strength and a greater release height. In javelin, a greater height leads to a greater maximum acceleration force on the javelin, a longer contact time with the javelin due to greater reach, and a greater height at release (O’Connor et al., 2007; Samaras, 2007c).

In swimming, a tall athlete experiences less wave resistance and therefore needs less strength and energy. Another benefit are longer arms and legs, as well as bigger hands and feet of tall swimmers, since they can pull or kick more water (Kjendlie & Stallman, 2011).

These advantages of short or tall human height are mainly biomechanical benefits giving a shorter or taller athlete a competitive edge over their opponent. Though these benefits are more significant in some sports than in others, these advantages or disadvantages can be balanced out in some sports by other components like a higher skill level. This is especially valid in sports that heavily rely on technical components, or leaner body physique (Samaras, 2007b, 2007a). However, the anthropometric data of elite Olympic athletes (see table 4, 5 and 6) indicate that in certain sports, taller or smaller athletes are indeed more successful, whereas in others, height might not be much of a discriminating factor (Wood, 2018b, 2018a).

1.6.3 Average height of Olympians

The average height of women worldwide is 1.59 m and 1.67 m in Austria. The mean height for female Rio Olympic athletes was above average with 1.70 m and the mean height for medallists was higher with 1.72 m (NCD Risk Factor Collaboration, 2023; Wood, 2018b).

Table 4: Mean, smallest and tallest height of all female participants and all female medallists of the 2016 Rio Olympic Games (Wood, 2018b).

Sport	mean height [cm]	Min. height [cm]	Max. height [cm]	mean height medallist [cm]	Medallist min. height [cm]	Medallist max. height [cm]
All female events	170	133	203	172	140	203
Aquatics	172	143	194	173	153	194
Archery	168	153	180	168	158	180
Athletics	169	133	193	171	152	193
Badminton	169	156	183	171	156	183
Basketball	183	161	203	185	167	203
Boxing	168	150	180	169	157	180
Canoe	170	153	181	171	161	181
Cycling	167	155	185	169	158	185
Equestrian	168	151	185	169	162	175
Fencing	171	152	185	174	165	185
Field Hockey	167	152	196	170	152	196
Football	168	153	188	170	153	180
Golf	169	158	183	170	168	172
Gymnastics	162	133	181	162	140	177
Handball	176	161	192	176	165	188
Judo	167	150	186	167	150	182
Modern Pentathlon	170	159	182	177	168	182
Rowing	177	150	196	179	150	193
Rugby Sevens	168	153	186	169	158	180
Sailing	169	152	184	170	157	184
Shooting	165	149	181	167	155	181
Table Tennis	165	149	181	163	150	174

Sport	mean height [cm]	Min. height [cm]	Max. height [cm]	mean height medallist [cm]	Medallist min. height [cm]	Medallist max. height [cm]
Taekwondo	173	159	188	176	164	188
Tennis	173	159	186	174	165	186
Triathlon	168	153	180	171	166	168
Volleyball	183	159	202	187	170	201
Weight lifting	160	137	178	159	145	178
Wrestling	165	150	180	164	151	175

The mean global height of men is 1.71m and 1.79 m in Austria. The mean height for male Rio Olympic athletes was above average, with 1.82 m for all athletes and 1.84 m for medallists (NCD Risk Factor Collaboration, 2023; Wood, 2018b).

Table 5: Mean, smallest and tallest height of all male participants and all male medallists of the 2016 Rio Olympic Games (Wood, 2018b).

Sport	Mean height [cm]	Min. height [cm]	Max. height [cm]	mean height medallist [cm]	Medallist min. height [cm]	Medallist max. height [cm]
All male events	182	145	218	184	150	215
Aquatics	186	153	208	189	164	206
Archery	180	164	194	180	174	186
Athletics	181	145	208	184	167	207
Badminton	181	167	198	180	170	194
Basketball	200	181	218	201	183	215
Boxing	176	152	206	177	152	206
Canoe	182	159	202	184	166	202
Cycling	179	164	196	182	166	191
Equestrian	179	161	196	179	168	193
Fencing	183	165	205	185	171	197
Field Hockey	180	161	196	181	172	193
Football	179	160	196	179	169	194
Golf	179	160	196	185	167	194
Gymnastics	168	152	184	166	155	180
Handball	191	177	210	194	179	210
Judo	178	155	210	180	160	203
Modern Pentathlon	183	172	197	185	178	192
Rowing	190	152	209	191	169	207
Rugby Sevens	183	168	198	183	171	198
Sailing	181	165	204	183	170	197
Shooting	178	160	202	176	167	189
Table Tennis	179	162	198	176	162	186

Sport	Mean height [cm]	Min. height [cm]	Max. height [cm]	mean height medallist [cm]	Medallist min. height [cm]	Medallist max. height [cm]
Taekwondo	186	160	207	189	178	207
Tennis	186	172	204	186	174	198
Triathlon	179	166	191	178	170	184
Volleyball	196	172	211	198	180	209
Weight lifting	171	148	197	170	150	197
Wrestling	176	152	203	168	160	198

However, some events seem to favour smaller and some taller athletes (see figure 6 and 7). In other events, no clear distinction between success and the height of the athletes can be found (Wood, 2018b). The aquatics category combines all 34 (17 female and 17 male) swimming and 8 (4 female and 4 male) diving events. Therefore, the mean values do not depict a clear distinction between tall swimmers and smaller divers. The same goes for the athletics category, where all track and field events are combined (International Olympic Committee, 2023a).

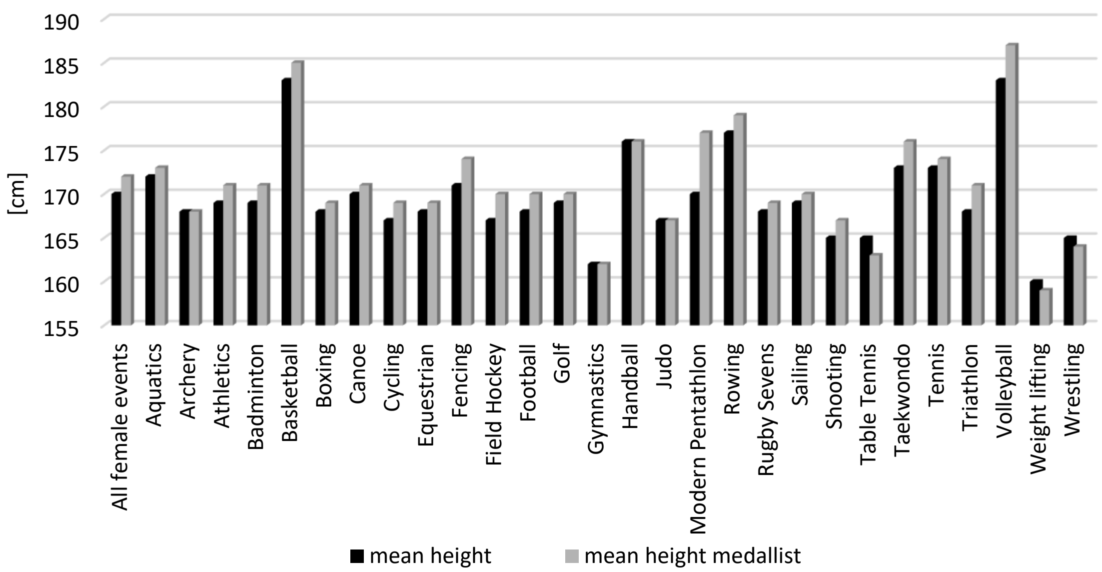

Figure 6: Comparison of mean height of all female Olympians and female medallists.

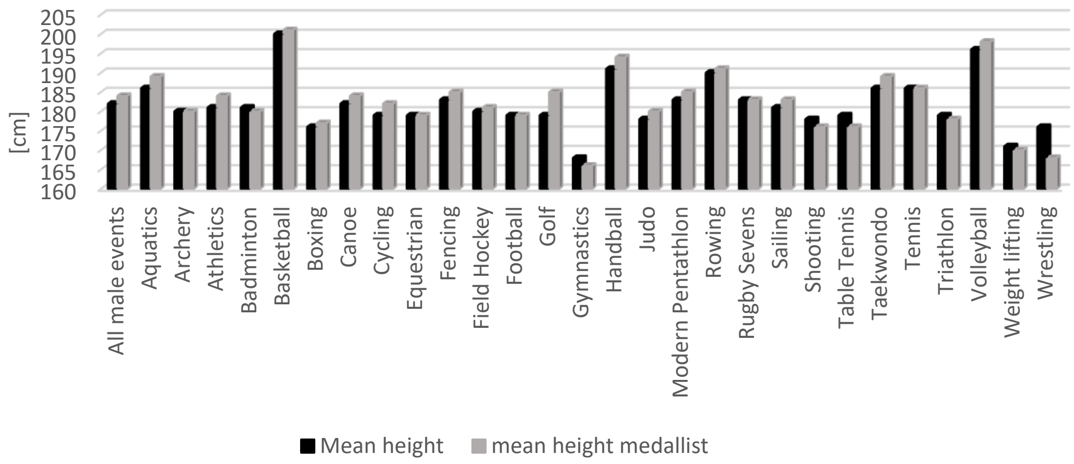

Figure 7: Comparison of mean height of all male Olympians and male medallists.

Nevertheless, there are several sports, including basketball, fencing, handball, modern pentathlon, rowing, taekwondo, tennis, and volleyball, showing athletes heights way above the global average. Additionally, the mean height of medallist in these events was even larger, making taller athletes in these sports more successful (Wood, 2018b). In the sports gymnastics, table tennis, weightlifting and wrestling, a contrary effect can be observed. The athletes' height was clearly below the average of athletes' overall height, with even smaller heights of the medallists, indicating a benefit of a smaller height in these events (Wood, 2018b).

Table 6: Mean height of male and female participants of the 2014 Sochi Olympic Games (Wood, 2018a).

Sport	average female height [cm]	average male height [cm]
All events	167	181
Alpine Skiing	169	180
Biathlon	166	180
Bobsled	173	185
Cross Country Skiing	167	180
Curling	166	180
Figure Skating	160	177
Freestyle Skiing	165	177
Hockey	168	185
Nordic Combined	-	179
Luge	172	181
Short-Track Skating	166	176
Skeleton	167	182
Ski Jumping	165	178
Snowboarding	167	179
Speedskating	169	180

In the Sochi 2014 Olympic Games, athletes' height did not deviate that far from the population's mean height values, considering that most participants of the winter Olympic Games are European, Northern American, Australian, Chinese, Japanese or Korean (International Olympic Committee, 2023b; Wood, 2018a). Only male ice hockey players tend to be clearly taller and female figure skaters clearly smaller than the mean heights (Wood, 2018a).

Even though height seems to be a crucial anthropometric characteristic for success in some sports, there are still several other components to consider when it comes to success in sports. To better understand these unique sport requirements, a performance-needs analysis should be carried out including the evaluation of technical, tactical, psychological, and physical demands. However, this task can be very difficult due to the complex nature of many sports (Till & Baker, 2020).

1.7 Handball

Handball is regarded as one of the most popular team sports in Europe and worldwide there are more than 19 million players. The game originated in the early 19th century in Scandinavia. For men, it became an Olympic sport in 1972 at the Games in Munich and four years later in 1976 in Montreal for women (Saavedra, 2018).

Handball is a demanding intermittent sport, with repeated sprints, changes of direction, jumps and throws with maximal intensity. In Handball there are usually four different positions: goalkeepers, backcourts, centre backs, pivots and wings (Karcher & Buchheit, 2017; Krüger et al., 2014). Due to specific tasks for each position, anthropometric profiles for the sport vary significantly (Leuciuc et al., 2022).

In 2022 Leuciuc et al. analysed anthropometric data from the top-four ranked male teams over a time span of 18 years (2004-2021). They found that the wings on average are the shortest (185.2 cm) and lightest players (84.5 kg) and pivots the tallest (197.1 cm) and heaviest (105.1 kg). Backcourts are on average 196.2 cm tall and weigh 98.6 kg. Goalkeepers average close to the height of pivots and backcourts with 194.4 cm and close to the weight of backcourts with 97.3 kg. Centre backs are taller and heavier than wings but smaller and lighter than pivots, backcourts, and goalkeepers with an average height of 190.3 cm and average weight of 92.7 kg. Overall, the body height and body weight are 192.6 cm and 95.3 kg. This mean height increased during the 18-year assessment period from 190 cm and the mean weight from 90.5 kg. On Average handball players are taller than the general population, as only around 25% of the male population would meet these eligibility criteria.

Similar results were reported for female handball players. A review by Čižmek et al. (2013) and Manchado et al. (2013) revealed that players with a higher skill level were taller than amateur players, or players at a lower level of competition, and taller than the population average (NCD Risk Factor Collaboration, 2023). Furthermore, as seen in men's teams, wing players tend to be the smallest and goalkeepers the tallest players (Čižmek et al., 2013; Manchado et al., 2013). However, two studies found no significant differences in the players' height regarding their playing positions (Hasan et al., 2007; Vila et al., 2012). A greater height of elite players compared to players of lower levels can already be found in youth handball at the age group of Under-16 (Mohamed et al., 2009; Moss et al., 2015).

The differences in height of the various playing positions, especially in male teams, stem from the specific requirements of each position (Manchado et al., 2013). The higher weight of pivots and backcourt players can be accounted to the higher muscular mass than wings (Leuciuc et al., 2022). The larger height of goalkeepers is important for good coverage of the goal, as a taller player is able to block a greater area of the goal (Krüger et al., 2014; Zapartidis et al., 2011). For pivots, a large but not obese body is of benefit since it offers greater stability. Furthermore, it gives the players an advantage against collisions, pushes and tough contacts of the defence (Krüger et al., 2014). Wings as well as backs on the other hand need speed, acceleration and jumping power. A high body mass might therefore be unfavourable. Wings are usually the smallest and lightest handball players, which might give them an advantage for fast changes of direction and short horizontal accelerations. Backs, on the other hand, are taller so they have a greater vertical jumping height and can throw over the defensive wall (Mellwig et al., 2009). However, other skills like coordination, speed, power, and mental ability can compensate for lower body height (Táborský, 2007).

Nevertheless, there are significant correlations between a taller height and important performance characteristics in handball. Studies found a strong positive correlation of height and throwing velocity (Debanne & Laffaye, 2011; van den Tillaar & Ettema, 2004). In duels with an opponent, a taller stature brings advantages in handling, stealing and throwing the ball (Táborský, 2007), and in tough direct contacts (Bencke et al., 2002). Furthermore, longer limbs are of benefit for dribbling, catching and passing the ball (Skoufas et al., 2003).

In general, elite male and female players are taller and have an overall better physiological profile. Furthermore, they have a higher degree of fat-free mass, are part of the endomorph, mesomorph, and somatotypes, and have a larger muscular mass than players of lower levels (Debanne & Laffaye, 2011; Konstantinos et al., 2019; Leuciuc et al., 2022; Manchado et al., 2013; Wagner et al., 2021).

When it comes to the nutritional status of handball players, a great range of and contradictory results can be found. The mean BMI and body fat percentage of elite male players (Leuciuc et al., 2022; Lidor & Ziv, 2018; Lijewski et al., 2019) and of elite female players (Konstantinos et al., 2019; Lidor & Ziv, 2018) are considered to be in a normal, athletic range (Jeukendrup & Gleeson, 2019). Furthermore, handball falls into the classification of non-lean sports (Miralles-Amorós, Vicente-Martínez, et al., 2023).

A study by A. M. Silva et al. (2017) followed handball players over a whole athletic season and found a positive energy balance for the players. However, in a recent study by Miralles-Amorós et al. (2023), low energy availability (LEA) (<30 kcal/lean mass per day) in all female professional players has been observed. Despite their low caloric intake, all of them had eumenorrhea. A review by Castillo et al. (2022) showed that female and male handball players did not meet the overall recommendations for energy intake but they met the recommendations for protein intake. A similar review by Mora-Fernandez et al. (2022) also found that the nutritional intake of male and female handball players did not meet the recommendations to cover the physical activity demands. While some of these athletes exhibited signs of eating disorders, the prevalence of eating disorders in handball players seems to be below the average generally observed in athletes (Baldó Vela et al., 2021; Miralles-Amorós, Vicente-Martínez, et al., 2023).

1.8 Combat sports

Combat sports are a class of competitive contact sports where the winner is determined by prearranged rules and using specific, regulated techniques (Barley et al., 2019; Noh et al., 2015). They are well liked all over the world with their popularity as a sport steadily increasing (Gürsoy & Canli, 2021). Reasons for the growing popularity include improving balance, flexibility and strength, maintaining physical fitness and gaining health benefits (Norjali, 2019).

At the Tokyo 2020 Olympic Games, combat sports with weight categories (Boxing, Judo, Karate, Taekwondo, Wrestling) made up 62 of the 339 available gold medals (International Olympic Committee, 2022). They occupy a significant space in the sports world with several other big tournaments, including the World Combat Games and world championships of each combat sport (Tabben et al., 2014).

Combat sports can be classified into striking/kicking (e.g. Boxing, Karate, Kickboxing, Kung-fu and Taekwondo), grappling/throwing (e.g. Aikido, Brazilian jiu-jitsu, Judo and Wrestling) and hybrid combat sports that combine both styles (e.g. Mixed Martial Arts) (Hammami et al., 2018). In striking combat sports the athletes try to land hits with their feet/legs or their hands with a single punch or combinations (Reale et al., 2020; J. J. R. Silva et al., 2011), while in grappling combat sports they try to grip or throw their opponent to the ground forcing them to submit through ground combat, chokeholds or joint locks (Ratamess, 2011; Reale et al., 2020).

Every combat sport has a different set of rules and regulations, varying scoring systems and durations, therefore, each combat sport has different physiological requirements (Norjali, 2019; Tack, 2013). Most combat sports require tactical skills, an excellent technique, and physical fitness including strength, high aerobic capacity, power, and speed (Tabben et al., 2014). Additionally, most disciplines require a good mobility and flexibility for optimal execution of different techniques (Franchini & Herrera-Valenzuela, 2021). Matches are intermittent physical activities, alternating between high- and low-intensity periods (Matsushigue et al., 2009), and require a maximal effort of the combatants (Bali, 2015). This, however, might lead to increased levels of anxiety and mental stress (Piskorska et al., 2017).

Apart from these physiological, technical, and tactical skills, anthropometry is another important factor depending on the type of combat sport. In the striking sports Karate, Boxing and Taekwondo height and length are important for future success. Studies show that elite athletes have longer limbs than non-elite combatants (Giampietro et al., 2003; Kazemi et al., 2006). Height advantage might help facilitate reaching or striking the opponent. For judokas for example height is not as important since there are different techniques for short and tall athletes. Tall athletes usually prefer leg techniques while short to medium-height judokas tend to prefer hand techniques (Lech et al., 2007).

A characteristic of most combat sports is that athletes are divided into weight categories in order to ensure fights between athletes of similar size to even the playing field somewhat (Barley et al., 2019). Therefore, it is mandatory for athletes to weigh-in before and sometimes during a competition (Thomas et al., 2021), with duration between the weigh-in and the actual competition varying between combat sports (Reale et al., 2017a). However, combat sports athletes try to gain a theoretical physical and mental advantage by being paired with an opponent that is lighter than their own day-to-day weight (Barley et al., 2018; Gann et al., 2015). Hence, they cut weight in the weeks or days before the weigh-in and afterwards try to regain weight prior to the start of the fights. This practice is called making weight or weight-cutting (Artioli, Gualano, et al., 2010; Barley et al., 2018).

1.8.1 Making Weight

Making weight is a common practice in combat sports (Štangar et al., 2022) and depends on the nature of each sport as well as their different rules (Matthews et al., 2019; Reale et al., 2017a). The time range between weigh-in and competition varies significantly between sports (2-32h, see table 7) and therefore also influences possible recovery (Burke et al., 2021).

Table 7: Characteristics, weight categories and weigh-in regulations of different combat sports (Burke et al., 2021; Mellbye, 2023; Reale et al., 2017a)

Combat sport	Characteristics	Weight categories	Weigh-in
Boxing – amateur / "Olympic" (Variations for other associations possible)	W = 3 rounds, each 3 min M = 3 rounds, each 3 min Tournament over several days	Amateur by IBA: W = 12, M = 13 Olympic: W = 5, M = 8	- On the first day (morning) - on every contest day (morning) - less than 3 h between weigh-in and competition
Boxing – professional (Variations for other associations possible)	12 rounds W: 2 min per round M: 3 min per round	WBC: W = 16, M = 18	- 30, 14 and 7 days before: no more than 10% over the division limit 30 days before fight, 5% 14 days before and 3% 7 days before the fight - official weigh-in one day before the fight - weigh-in on competition day: no more than 10% weight gain compared to previous day
Brazilian jiu-jitsu (Variations for other associations possible)	- Several bouts over multiple days or on a single day - Match length varies between belt levels: White belt: 5 min Blue belt: 6 min Purple belt: 7 min Brown belt: 8 min Black belt: 10 min	IBJJF: W = 9, M = 10	20-30 min before the first bout
Judo	All bouts (4 to 8) on single day W = 4 min M = 4 min	W = 7, M = 7	- evening before competition - random checks on the morning of the competition: no more than 5% over weight division limit – otherwise disqualification
Karate	Kata: 45 sec – 2 min Kumite: W = 2 min, M = 3 min	Non-Olympic elite competitions: W = 5, M = 5 Olympic games: W = 3, M = 3	Day before competition start

Combat sport	Characteristics	Weight categories	Weigh-in
Kickboxing (Variations for other associations possible)	In a tournament: 3 rounds, each 2 minutes Single bouts: 5 rounds, each 2 minutes	WKO: W = 7 M = 10	Usually 24 hours before a competition, Same day weigh-ins possible
Mixed martial arts – MMA (Variations for other associations possible)	Non-championship fights: 3 rounds, each 5 minutes Championship fights: 5 rounds, 5 minutes	Unified weight classes: 14 classes UFC: W = 4 M = 8	- morning of the day before a fight - Non-championship fights: No more than 1 pound over weight class limit - Championship fights: No more than 0,5 pounds over weight class limit - doctors can pull fighters if they are dehydrated
Muay Thai (Variations for other associations possible)	W = 5 rounds, each 2 min M = 5 rounds, each 3 min	WBC: W = 11 M = 17	Day before fight
Taekwondo	Tournament on single day, 4-8 bouts, W = 3 rounds, each 2 min M = 3 rounds, each 2 min	World Championships: W = 8, M = 8 Olympic Games: W = 4, M = 4	Evening before a competition
Wrestling – Freestyle	Tournament over 2 days, 4-8 bouts, W = 2 rounds, each 3 min M = 2 rounds, each 3 min	UWW: W = 10, M = 10 Olympic Games: W = 6, M = 6	On the morning of the competition
Wrestling – Greco-Roman	Tournament over 2 days, 4-8 bouts, W = 2 rounds, each 3 min M = 2 rounds, each 3 min	UWW: M = 10 Olympic Games: M = 6	On the morning of the competition

W = women; M = men; IBA = International boxing association; IBJJF: international Brazilian jiu-jitsu federation; UFC: ultimate fighter championship; UWW: united world wrestling; WAKO: world association of kickboxing organizations; WBC: world boxing council.

Depending on the type of combat sport, the age and level of competition, making weight has a prevalence from 25 to 94% for both male and female athletes (Lakicevic, Matthews, et al., 2022). In grappling sports, the influence of body mass and regaining said body mass after the weigh-in seems to be more beneficial than in striking sports (Lakicevic, Reale, et al., 2022). Weight loss before a weigh-in ranges from 2% to 10% (Artioli et al., 2016) and frequency of making weight ranges from weekly (e.g. collegiate wrestling during their competitive season), to a couple of times a year, since athletes usually only have a limited number of fights (e.g. professional boxing) (Burke et al., 2021). The most commonly used methods include energy intake restriction, total body fluid reduction, increasing sweat response (e.g. heated wrestling, plastic suits, saunas, spitting), laxatives, diet pills, diuretics, enemas, water loading, and bulimia (Artioli, Scagliusi, et al., 2010; Burke et al., 2021; Kiningham & Gorenflo, 2001). Common among all combat sports is the chronic strategy of energy intake restriction with gradual dieting and an increased amount of exercise, less common is fasting and skipping meals (Barley et al., 2018; Reale et al., 2018). Manipulations in a short period of time (days or hours) are called rapid weight loss or acute weight loss. Acute strategies to rapidly loose body weight are manipulation of body fluids, gastrointestinal tract contents, and glycogen stores (Burke et al., 2021). The most common methods are fluid intake restriction and methods to increase the sweat production, like saunas and using sweatsuits. This can lead to a loss of over 5% body mass within 24 hours (Barley et al., 2018; Brito et al., 2012; Crighton et al., 2016; Reale et al., 2018).

After the weigh-in combat sport athletes try to rapidly regain or renew body fluids, glycogen stores, and electrolytes before the competition (Lakicevic et al., 2021). The strategies for regaining the weight are dependent on the magnitude and type of weight loss and time between weigh-in and competition (Reale et al., 2017b). If the recovery time is not sufficient to fully recover, prioritisation of important nutrients and nutrients that do not lead to discomfort should be made (Burke et al., 2021).

1.8.2 Implications of making weight on performance and health

As weight cutting is done before a competition, it is important to understand the implications on the performance and on the athlete’s health in general (Barley et al., 2019). Acute restrictions like fluid intake and increasing sweat production through exercise that reduce the weight by 2-3% have, in all probability, little to no disadvantages. Especially if the time between weigh-in and competition is long enough and appropriate recovery strategies are put into practice (Burke et al., 2021). Artioli et al. (2016) suggested that the competitive advantages of making weight might surpass the negative effects on performance, yet reducing weight more than 3% on the other hand might have serious negative implications on health status and performance (Burke et al., 2021).

The most serious consequence of making weight on the athlete’s health is death. Twenty-six years ago, a South Korean elite judoka died after trying to make weight with a hot sauna session in preparation for the 1996 Olympic Games in Atlanta (AP News, 1996). A year later, three American wrestlers died independently of each other by trying to lose a great amount of weight in a short time frame (Centers for Disease Control and Prevention (CDC), 1998). In 2013 a mixed-martial arts fighter was found dead after he tried to lose the last kilogram to reach his goal weight (Cruz, 2013). In 2017, an 18-year-old female Muay Thai fighter died after trying to cut a substantial amount of weight for a weigh-in the following day (Menagh, 2020). In 2018, a 16-year-old taekwondo athlete collapsed and died during competition. He was taking medication to lose weight and it is widely believed that he collapsed due to a heart attack triggered by rapid weight loss prior to the fight (Forsyth, 2018). These tragic events are associated with cardiovascular issues or heat stroke due to total body fluid reduction methods (AP News, 1996; Centers for Disease Control and Prevention (CDC), 1998; Cruz, 2013; Forsyth, 2018; Menagh, 2020).

Dehydration can lead to an increased possibility of acute cardiovascular complications, stroke or heat stroke, and ischemic heart disease (Artioli et al., 2016; Barley et al., 2019) due to reductions in blood plasma and total blood volume (Cheuvront et al., 2010; Cheuvront & Kenefick, 2014). These plasma volume changes may also impair aerobic abilities due to reductions in haemoglobin mass (Reljic et al., 2013, 2016). Additionally, severe dehydration may alter brain morphology and therefore increase the risk of serious brain injury in a fight (Crighton et al., 2016). Acute dehydration may furthermore have a negative effect on neuromuscular functions by influencing the electrolyte concentration and consequently the fluid balance of the cell (Sjøgaard, 1986). Studies showed that after an acute dehydration, 24 hours are not enough time to fully recover one's hydration status. It might therefore still affect the athlete's performance in the competition since the time between the weigh-in and the competition is usually under 24 hours (Jetton et al., 2013; Martínez-Aranda et al., 2023).

Interpretation of study results and their implications on performance and health proves challenging since most studies about the advantages and disadvantages of making weight are carried out under laboratory conditions, use different strategies or only single ones, have varying recovery periods, and varying magnitudes of weight loss (Burke et al., 2021). Furthermore, making weight has different effects on male and female athletes (Martínez-Aranda et al., 2023) and mixed results have been reported on various performance variables (Barley et al., 2019; Brechney et al., 2022; Bueno et al., 2022). However, performance in combat sports is also affected by variables not directly associated with making weight like athletic ability, conditioning, skill level, tactics and psychological factors such as confidence, determination and coping with stress (Gann et al., 2015). Therefore, it is challenging to interpret the actual influence of weight cutting on performance (Brechney et al., 2022).

Mixed results have also been reported on the psychological factors of making weight. Participating in rapid weight loss seems to have a positive influence on the sports identity, focus, and the sense of belonging. Furthermore, it might serve as a coping mechanism to deal with stress (Gonçalves et al., 2021; Pettersson et al., 2013), though contrarily, rapid weight loss can also induce mental stress (Barley et al., 2019). However, it has been identified that elite combat sport athletes have higher levels of mental toughness, determination, and confidence (Andreato et al., 2022; Bueno et al., 2022).

Low levels of muscle glycogen induced by acute energy intake reduction might lead to physical and mental fatigue since it impairs the coupling of excitation and contraction in muscle cells (Ørtenblad et al., 2013; Reale et al., 2017b). This might further influence decision-making skills, attention, and anticipation (Martínez-Aranda et al., 2023; Uddin et al., 2022).

If these energy restrictions are prolonged, exercise performance could be negatively affected through physiological changes of the lipid and carbohydrate metabolism (Burke, 2015; Odland et al., 1998; Westman et al., 2007). Other negative health effects of repeated bouts of rapid weight loss include reduced insulin sensitivity, impaired renal and immune function, imbalances of the hormonal system, and bone loss (Artioli et al., 2016; Barley et al., 2019; Ceylan et al., 2022).

Health consequences are therefore not only a concern for acute weight loss strategies, but also for chronic weight loss, especially with a chronic negative energy balance. Most combat sports athletes use acute as well as chronic weight loss practices (Barley et al., 2019). A negative energy balance will lead to the state of low energy availability (LEA), where the body does not have sufficient energy in order to support all functions needed to attain or maintain optimal performance and health (Mountjoy et al., 2018; Wasserfurth et al., 2020).

Athletes in general are at a higher risk to experience LEA, the reasons for this are manifold and include sociological, psychological, and behavioural aspects (see figure 8) (Melin et al., 2019).

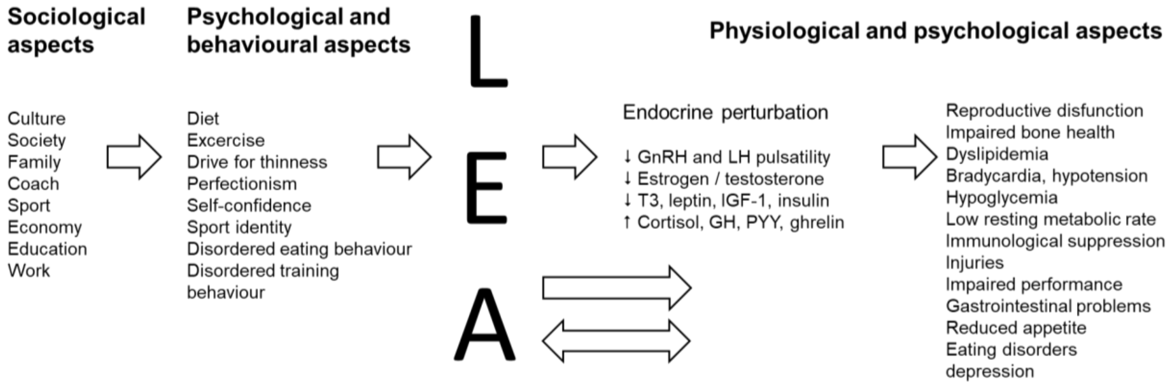

Figure 8: Potential sociological, psychological, and behavioural causes and effects of LEA in athletes. Adapted from (Melin et al., 2019)

Examples are body dissatisfaction, lack of knowledge and time, finances, loss of appetite after training, altered dietary behaviours turning compulsive, belief of better performance with lower body weight, social pressure, and pressure from teammates and coaches

(Wasserfurth et al., 2020). However, LEA might occur with or without an eating disorder (Melin et al., 2015).

These reasons for LEA can lead to several potential consequences on sports performance via direct or indirect pathways. They include decreased endurance performance, increased injury risk, decreased training response, impaired judgment, decreased coordination, decreased concentration, irritability, depression, decreased glycogen stores, and decreased muscle strength (Mountjoy et al., 2018).

In addition to several consequences on sports performance, LEA might negatively interfere with physiological functions such as immunological, gastrointestinal, haematological, cardiovascular, endocrine, metabolic, and menstrual function, as well as bone health, growth and development, and psychological consequences. All these impairments contribute to syndrome relative energy deficiency in sports (RED-S) (V.-P. Boisseau et al., 2005; Mountjoy et al., 2018). RED-S can occur in both sexes but with varying biological impairments and prevalence. Additionally, it has been suggested that LEA is higher in female athletes (Mountjoy et al., 2018).

LEA may lead to negative health effects on bone health, especially in women. Consequently, bone mineral density and estimates of bone strength might decrease, bone microarchitecture and bone turnover markers might change, and the risk of bone stress injuries might increase (Mountjoy et al., 2018). Interestingly, studies showed that bone mineral density in combat sports athletes is higher than in the general population. Hence, the physical impacts and weight bearing activities in combat sports might have a more beneficial effect on bone health than the negative effect of LEA (Lakicevic, Reale, et al., 2022; Sagayama et al., 2020). However, in LEA, iron deficiency might further interact with bone health by dysregulating the GH/IGF-1 axis as well as with hypoxia and hypothyroidism (Petkus et al., 2017).

LEA might furthermore cause an impaired endocrine system including changes on the thyroid function, disturbances of the hypothalamic-pituitary-gonadal axis, alterations in hormones regulating the appetite, increases in GH resistance, decreases in IGF-1 and insulin, and elevated cortisol levels. Changes to appetite-regulating hormones include elevations in ghrelin, peptide YY and adiponectin, and a decrease in leptin and oxytocin levels (Allaway et al., 2016; Logue et al., 2020; Loucks & Thuma, 2003; Misra, 2014). These hormonal changes might be the body’s way to conserve energy for vital processes and functions (Jasienska, 2003; Wade & Jones, 2004) and might negatively influence growth and development of adolescents (Mountjoy et al., 2018).

1.8.3 Making weight in adolescent combat sport athletes

Most combat sports athletes, including adolescents, compete in a weight category below their "natural" weight (V.-P. Boisseau et al., 2005). Some combatants start to engage in making weight as early as four years old (Artioli, Gualano, et al., 2010; Berkovich et al., 2016). Young athletes seem to be mainly influenced to engage in weight cutting behaviour by their coaches and fellow athletes (Barley et al., 2019; Lakicevic, Reale, et al., 2022). The weight loss of adolescent combat sport athletes makes up about 1-6% of their body mass before a competition. Around 25-80% of young athletes participate in the practice, with numbers increasing with age (Berkovich et al., 2016; Viveiros et al., 2015). In different studies, junior combat sport athletes reported headaches, nausea, dizziness, nose bleeds, increased heart rate, hot flashes, fatigue and muscle pain after rapid weight loss (Alderman et al., 2004; Zubac et al., 2018). The tools used to lose weight are identical to adult athletes (Lakicevic, Reale, et al., 2022), however, adolescents have a different, not yet mature sweating function. Adults regulate body temperature by sweating through evaporative cooling whereas children increase the peripheral blood redistribution. This leaves them with a higher probability for heat strokes, since their core body temperature rises more easily especially in extreme conditions like saunas (Falk & Dotan, 2008; Lakicevic, Reale, et al., 2022).

Weight cutting can also negatively alter the protein status and can lead to a temporary negative nitrogen balance. Thus, making growth disruptions a possibility (N. Boisseau, 2006). Especially concerning is the behaviour of some adolescent athletes who try to stay in a certain weight category that is lower than their natural physiological body weight between competitions for two years or longer. This practice puts them at risk for negative implications on growth and development (Berkovich et al., 2016) particularly during their peak height velocity. The consequent energy deficiency may not only stunt their growth, but may further negatively influence their physical performance as well as their metabolic system (Berkovich et al., 2016; Mountjoy et al., 2018).

The absolute energy requirements peak in the late teens, but optimal nutrition is important during the whole childhood and adolescence, even more so for physically active athletes. Their additional energy requirements put them in danger of chronic LEA (Lakicevic, Reale, et al., 2022), which might decrease their IGF-1 levels, elevate their GH levels and increase their GH resistance (Fazeli & Klibanski, 2014). Furthermore, adolescent athletes with LEA had a higher percentage of presenting with psychosomatic disorders, decreased ability to cope with stress, mild depressive traits, and fear of weight gain (Bomba et al., 2007, 2014; Marcus et al., 2001).

1.8.4 Disordered eating and eating disorders

The challenge of making weight and the consequent fixation on controlling one's body weight over a long period of time might be a contributing factor in developing eating disorders or disordered eating in combat sport athletes (Berkovich et al., 2019). Studies indicate that weight-class athletes are in one of the highest risk groups for developing disordered eating behaviour (de Borja et al., 2021; Thomas et al., 2021). Compared to an eating disorder, disordered eating falls short of meeting the clinical diagnosis. However individuals with disordered eating might present with an abnormal eating behaviour, use methods of extreme weight regulation, and show an obsession with diets, their body, and food (Nattiv et al., 2007; Wells et al., 2020).

In general, athletes present with a higher percentage of eating disorders or disordered eating than the non-athlete population, especially in weight-sensitive sports (Vasiliu, 2023). Furthermore, it is one of the most prevalent disorders during adolescence (Herpertz-Dahlmann, 2015; Pustivšek et al., 2019). Other risk factors include personality traits like perfectionism and obsessiveness, doubts about one's own abilities, external social influence to become thinner, self-perceived body image, early start of sport-specific training, rules and regulations of a sport, and negative behaviour of a coach (Forsberg & Lock, 2006; Sundgot-Borgen & Torstveit, 2010; Vasiliu, 2023). Perfectionism in sports has not only been linked to eating disorders, but also to stress, anxiety and compulsiveness (Torres-McGehee et al., 2020).

2 Methods

Since making weight might influence growth of adolescent athletes and irregularities were found in the height prediction data of combat sports athletes at Leistungssport Austria, the aim of this master's thesis is to answer the research questions: "Does the predicted adult height of youth athletes match the actual body height as a grown-up?" and "Are there significant differences between the prediction and actual adult height in handball players and combat sport athletes?", with the hypothesis that the adult height prediction of combat sport athletes is less accurate than the adult height prediction of handball players.

To answer the research questions, the data of 22 female and 23 male handball and combat sports athletes were statistically analysed using IBM SPSS Statistics, version 29.0 (SPSS, Chicago, IL, USA). For this analysis, already existing data that has been recorded between 2015 and 2021 at routine exams at Leistungssport Austria were used. All participants signed a declaration of consent stating that the data can be used anonymously in retrospective studies such as this. Additionally, the study was ethically approved by the ethics committee of the University of Vienna. Radiographs of the wrist bones were obtained from the athletes at the age of 14 years. The adult height was then predicted by a trained sports medicine specialist using the Tanner Whitehouse TWII and TWIII method. Additionally, data of the body height and sitting height were measured once a year for five years in a row using the ISAK method. These data helped to track the growth and to eliminate measuring errors. At an adult age, the actual adult height of the participants was determined.

The data was tested for normal distribution using the Shapiro-Wilk-Test. The comparison between the estimated height and adult stature was then statistically analysed using the *t*-test for paired samples. Intergroup comparisons were performed using an independent sample *t*-test or a one-way analysis of variance (ANOVA) with a Bonferroni corrected post-hoc test. Two-sides p-values of <.05 were considered to be statistically significant for all calculations. Correlation coefficients of 0.7 to 1 were defined as strong, 0.4 to 0.7 as moderate, and <0.4 as weak (Akoglu, 2018). Additionally, the effect sizes Hedge's g was calculated using the formula $g = t \cdot \sqrt{\frac{n_1+n_2}{n_1 \cdot n_2}}$. A large effect was defined as >0.8, a medium as 0.5 to 0.8, and a small effect as 0.2 to 0.5 (Ellis, 2010). For the ANOVA, the effect size η^2 was calculated with a small effect from 0.01 to 0.06, a medium effect from 0.06 to 0.14, and a large effect >0.14 (Ellis, 2010).

Statistical power was obtained by using the programme G*Power 3.1 (Faul et al., 2007). Bland-Altman plots were constructed to assess the agreement between actual and predicted adult height.

3 Results

In total the data of 45 athletes has been analysed (see table 9). Of those 45 athletes, 22 were female and 23 male. 28 athletes were handball players, 16 female and 12 male, and 17 were combat sports athletes, 6 female and 11 male. Of the 17 combat sport athletes 14 were judokas and 2 female athletes did Taekwondo, and 1 male was a kickboxer. The results of the comparison between the estimated height and adult stature using the *t*-test for paired samples is listed in table 8 and depicted in figure 9. All data was normally distributed.

Table 8: Mean values and standard deviation of the predicted adult height, the adult height as well as the difference between the predicted adult height and the actual adult height including the p-value and statistical power in different groups.

Variable	n	Predicted adult height	Adult height	predicted height minus adult height	power
All athletes	45	176.7 ± 9.0 cm	175.5 ± 9.2 cm	-1.2 ± 2.6 cm (p = 0.003)**	0.85
Female athletes	22	170.7 ± 7.2 cm	169.8 ± 7.3 cm	-0.9 ± 1.9 cm (p = 0.032)*	0.57
Male athletes	23	182.5 ± 6.5 cm	181.0 ± 7.4 cm	-1.5 ± 3.2 cm (p = 0.033)*	0.58
Handball players	28	178.0 ± 8.7 cm	177.2 ± 8.9 cm	-0.8 ± 2.1 cm (p = 0.062)	0.48
Combat sports athletes	17	174.6 ± 9.3 cm	172.7 ± 9.3 cm	-2.0 ± 3.2 cm (p = 0.024)*	0.62
Female handball players	16	172.8 ± 6.9 cm	171.9 ± 7.1 cm	-1.0 ± 2.0 cm (p = 0.071)	0.40
Female Combat sports athletes	6	165.0 ± 4.8 cm	164.2 ± 4.4 cm	-0.9 ± 1.9 cm (p = 0.313)	0.14
Male handball players	12	184.8 ± 5.7 cm	184.3 ± 5.5 cm	-0.6 ± 2.4 cm (p = 0.437)	0.10
Male combat sports athletes	11	179.9 ± 6.5 cm	177.3 ± 7.8 cm	2.6 ± 3.7 cm (p = 0.045)*	0.55

* p<0.05; ** p<0.01

A significant difference between the predicted adult height of all athletes (176.7 ± 9.0 cm) and their actual adult height (175.5 ± 9.2 cm) was found (95% CI 0.44-2.02, T(44) = 3,14, p = 0.003). When separated by sex, a significant different between the estimated height (female = 170.7 ± 7.2 cm, male = 182.5 ± 6.5 cm) and final stature (female = 169.8 ± 7.3 cm, male = 181.0 ± 7.4 cm) of female (95% CI 0.09-1.76, T(21) = 2.30, p = 0.032) and of male athletes was found (95% CI 0.14-2.91, T(22) = 2.28, p = 0.033).

Table 9: Sex, sport, predicted height and deviation, adult height, and difference to the predicted height of all participants.

sex	sport	predicted height [cm]	deviation [cm]	adult height [cm]	predicted height minus adult height [cm]
female	Taekwondo	170	1.5	169.5	-0.5
female	Taekwondo	161	1.5	158	-3.0
female	Judo	169	1.5	167.6	-1.4
female	Judo	168	1.5	165.5	-2.5
female	Judo	164	1.5	164.3	0.3
female	Judo	158	3.0	160	2.0
female	Handball	164	1.5	164	0.0
female	Handball	168.5	1.5	168	-0.5
female	Handball	166	1.5	164	-2.0
female	Handball	170	1.0	164.5	-5.5
female	Handball	171	3.0	166.8	-4.2
female	Handball	165	1.0	163.7	-1.3
female	Handball	179	1.0	177.4	-1.6
female	Handball	170	2.7	170.5	0.5
female	Handball	168	1.0	169.5	1.5
female	Handball	174	1.5	175.6	1.6
female	Handball	176	2.5	177.2	1.2
female	Handball	175	1.5	174	-1.0
female	Handball	179	3.0	179.4	0.4
female	Handball	187	1.0	184.7	-2.3
female	Handball	185	1.5	183.5	-1.5
female	Handball	168	1.5	167.5	-0.5
male	Kickboxing	185	2.0	182.6	-2.4
male	Judo	177	3.7	173.3	-3.7
male	Judo	180	3.5	180.5	0.5
male	Judo	173	3.7	168.6	-4.4
male	Judo	178	3.7	183.1	5.1
male	Judo	176	3.5	166.8	-9.2
male	Judo	189	3.5	186.6	-2.4
male	Judo	176	3.5	172.5	-3.5
male	Judo	173	3.5	168	-5.0
male	Judo	179	3.7	180	1.0
male	Judo	193	3.5	188.6	-4.4
male	Handball	177	3.7	180.8	3.8
male	Handball	185	3.5	184.8	-0.2
male	Handball	180	3.7	181.7	1.7
male	Handball	188	3.5	187	-1.0
male	Handball	180	3.7	176	-4.0
male	Handball	186	3.2	186	0.0
male	Handball	185	3.5	188.3	3.3
male	Handball	194	3.5	192	-2.0
male	Handball	191	3.5	189.5	-1.5
male	Handball	177	3.0	174.8	-2.2
male	Handball	192	3.5	189.5	-2.5
male	Handball	183	3.7	180.9	-2.1

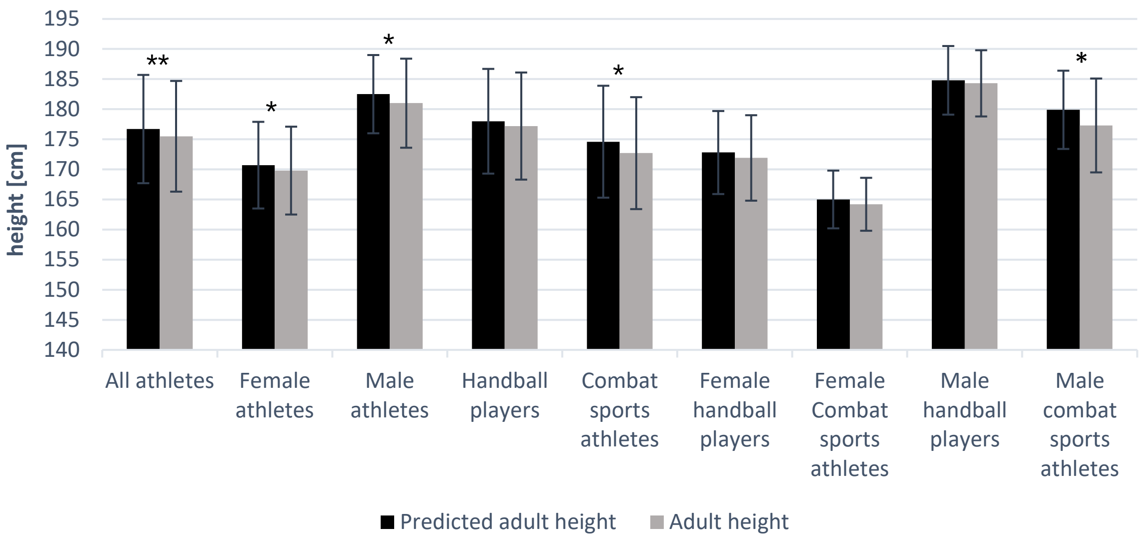

*Figure 9: Comparison of the predicted adult height and the actual adult height grouped by sex, sports or sex and sports. * p<0.05; ** p<0.01*

Figure 10 displays the Bland-Altman-plot of the differences between the predicted and the final height of all athletes against the mean height, with the representation of the limits of agreement (mean±1.96 SD; 3.9 and -6.4 cm). The differences between the predicted and the final height of all but two athletes are within these limits of agreement, with one male Judoka above (5.1 cm) and one male Judoka below (-9.2 cm).

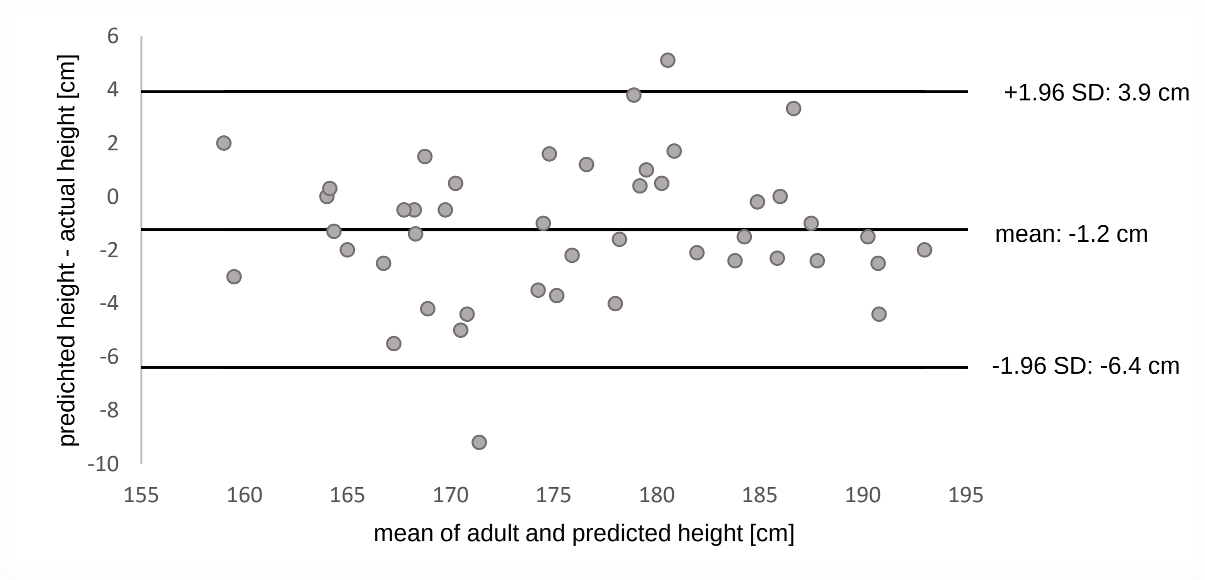

Figure 10: Bland-Altman plot of the differences between predicted and final height against the mean height, with the representation of the limits of agreement.

When separated by sport, no significant difference was found between the predicted adult height (178.0 ± 8.7 cm) and the actual adult height (177.2 ± 8.9 cm) of handball players (95% CI -0.04-1.61, T(27) = 1.95, p = 0.062). There was however a significant difference between the predicted adult height (174.0 ± 9.3 cm) and the actual adult height (172.1 ± 9.2 cm) of combat sports athletes (95% CI 0.16-3.73, T(15) = 2.32, p = 0.035).

Separated by sex and sport, no significant differences between estimated adult height (female: 172.8 ± 6.9 cm, male: 184.8 ± 5.7 cm) and adult stature (female: 171.9 ± 7.1 cm, male: 184.3 ± 5.5 cm) were found for female (95% CI -0.09-2.00, T(15) = 1.94, p = 0.071) or male handball players (95% CI -0.97-2.08, T(11) = 0.81, p = 0.437), nor for female combat sports athletes (estimated height: 165.0 ± 4.8 cm, adult height: 164.2 ± 4.4 cm) (95% CI -1.10-2.80, T(5) = 1.12, p = 0.313).

For male combat sports athletes however, there is a significant difference between the estimated (179.9 ± 6.5 cm) and the actual adult height (177.3 ± 7.8 cm) (95% CI 0.07-5.09, T(10) = 2.29, p = 0.045). All correlation coefficients were high and significant (see table 10). Results of the intergroup analysis of differences of predicted adult height and actual adult height are depicted in figure 11 and table 11.

Table 10: Correlation between predicted adult height and actual adult height in different groups

Variable	n	Correlation (R)	Two-sided significance (p)
All athletes	45	0.958	<0.001
Female athletes	22	0.966	<0.001
Male athletes	23	0.902	<0.001
Handball players	28	0.971	<0.001
Combat sports athletes	17	0.939	<0.001
Female handball players	16	0.961	0.009
Female combat sports athletes	6	0.923	<0.001
Male handball players	12	0.909	<0.001
Male combat sports athletes	11	0.878	<0.001

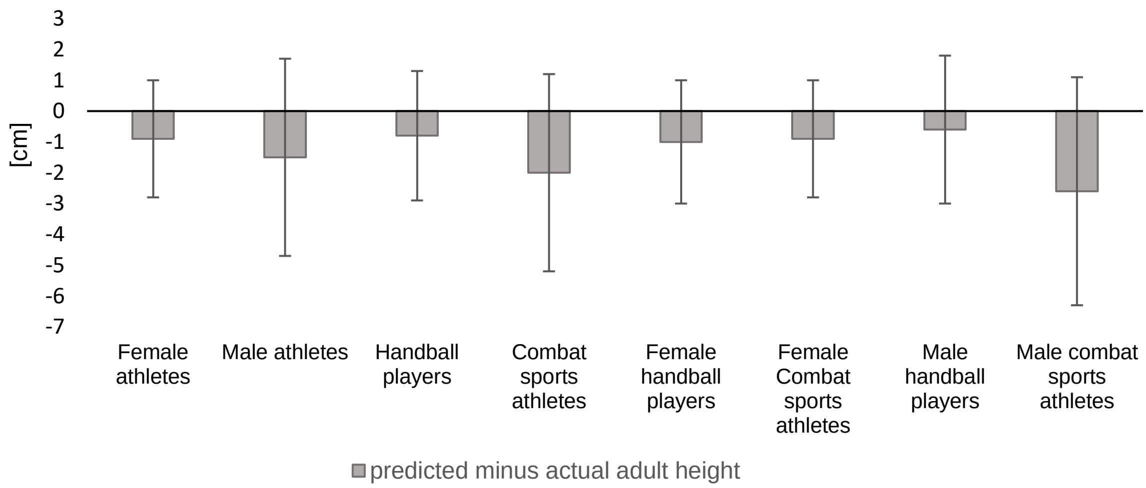

Figure 11: Mean values and deviation of the difference between the predicted and the actual adult height grouped by sex, sports or sex and sports.

Table 11: Mean values and deviation of the difference between the predicted and the actual adult height of different groups, with p-values, the effect size Hedge's g and the statistical power of the intergroup analysis.

Variable	n	Difference between predicted height and adult height	p-value	Hedge's g	power
female athletes	22	-0.9 ± 1.9 cm	0.449	0.23	0.12
Male athletes	23	-1.5 ± 3.2 cm			
Handball players	28	-0.8 ± 2.1 cm	0.144	-0,46	0.29
Combat sports athltes	17	-2.0 ± 3.2 cm			
Female handball players	16	-1.0 ± 2.0 cm	0.915	0.05	0.05
Female Combat sports athletes	6	-0.9 ± 1.9 cm			
Male handball players	12	-0.6 ± 2.4 cm	0.134	-0,65	0.31
Male combat sports athletes	11	-2.6 ± 3.7 cm			

The calculation of hedge's g showed a small effect between male and female athletes (g = 0.23, power = 0.12) and a small to medium effect between handball players and combat sport athletes (g = -0.46, power = 0.29). There is almost no effect between female handball players and female combat sport athletes (g = 0.05, power = 0.05) and a medium to large effect between male handball players and male combat sport athletes (g = -0.65, power = 0.31).

4 Discussion and Limitations

The results of this study include that no significant difference was found between the predicted adult height and the actual adult height in all handball players, male handball players and female handball players as well as in female combat sports athletes. A significant difference, however, was found for all female athletes and for all groups that include the male combat sports athletes. These groups are the male combat sports athletes themselves, all athletes, all male athletes, and all combat sport athletes. The intergroup analysis of differences between predicted adult height and actual adult height indicated no significant difference between any group. Nevertheless, a medium to large effect size was found between the male combat sports athletes and the male handball players.

TWII and TW3 height prediction models have been validated in several studies (Oh et al., 2009; Roemmich et al., 1997; Zachmann et al., 1978). In 2013 Ostojic validated the TWII method for athletic boys without growth disorders, with 135 Serbian boys participating in basketball, football, volleyball, or swimming for at least two years. In his study, the actual height of the athletes (185.6 ± 9.6 cm) was slightly underestimated by about 0.7 cm (184.9 ± 9.7 cm, 95% CI 1.61–3.01, $p = 0.55$) (Ostojic, 2013). However, no study known to the author so far validated the TWII/TW3 method for athletes competing in weight sensitive sports. Therefore, the athletes selected for this study were either participating in a weight sensitive sport (combat sports) or in the non-weight sensitive sport (handball) as a control group.

Unlike with Ostojic (2013), the TWII/TW3 method could not be validated for all athlete groups in this study. Contrary to his study, the actual adult height was, on average, slightly overestimated by 1.2 ± 2.6 cm (95% CI 0.44-2.02, $T(44) = 3,14$, $p = 0.003$). These different findings of either underestimation (Ostojic, 2013), or overestimation of the actual adult height might be due to a high inter-rater variability of manual height prediction methods like the TWII or TW3 method (Prokop-Piotrkowska et al., 2021). Similar findings to this study were reported by Joss et al. (1992) in a group of constitutionally tall boys. The TW method overestimated their final height by about 1 cm. They attributed this deviation to secular changes in skeletal maturation compared to the original sample the method is based on. Hence, the underestimation of the method in this study could be attributed to inter-rater variability and/or secular changes or other systematic errors.

When separated by sex, sports, or sex and sports, no significant difference between the predicted adult height and the actual adult hight was found for handball players (-0.8 ± 2.1 cm, $p = 0.062$), female handball players (-1.0 ± 2.0 cm, $p = 0.071$), female combat sport athletes (-0.9 ± 1.9 cm, $p = 0.313$) and male handball players (-0.6 ± 2.4 cm, $p = 0.437$).

This validates the height prediction method for all handball players and female combat sport athletes. However, due to the small sample size, the statistical power is rather low for these groups. Nonetheless, the mean difference between predicted and actual adult height in all groups is only 1.0 cm or lower and therefore even lower than the fluctuation range of the predicted height when using the TWII/TW3 method.

Furthermore, Straetemans et al. (2016) discussed the difference between statistical and clinical validation in their height prediction study, since a statistically significant difference might not be clinically relevant or vice versa. In sports, such clinical relevance could be a height difference that differentiates between successful, taller athletes and less successful, smaller athletes. Since in sports, success is often defined by winning a medal, statistically analysing the height difference between medallists and non-medallists in a sporting event like the Olympic Games could give an estimate of such a relevant height difference. Statistical analysis comparing the height of medallists and non-medallists of the 2016 Olympic Games of all handball players (1.7 ± 1.2 cm, $p = 0.162$), female handball players (0.3 ± 1.0 cm, $p = 0.738$), and female combat sport athletes (0.9 ± 1.0 cm, $p = 0.355$) showed no significant difference. This means that only height differences greater than these values might give athletes a competitive edge in these events (Wood, 2018b).

A significant difference between the height of medallists and non-medallists was found for male handball players (3.2 ± 1.2 cm, $p = 0.006$). However, the difference in this study between the actual height and the predicted height was only 0.6 ± 2.4 cm. Therefore, height differences of predicted and actual adult height of handball players and female combat sport athletes in this study are neither statistically significant nor do they seem to be significant to differentiates between successful and less successful athletes.

The TWII/TW3 height prediction method was however not validated for the group of all athletes (-1.2 ± 2.6 cm, $p = 0.003$), female athletes (-0.9 ± 1.9 cm, $p = 0.032$), male athletes (-1.5 ± 3.2 cm, $p = 0.033$), combat sport athletes (-2.0 ± 3.2 cm, $p = 0.024$), and male combat sport athletes (-2.6 ± 3.7 cm, $p = 0.045$), since a significant difference was found in these groups. As already discussed above, a height difference of -0.9 ± 1.9 cm for female athletes and -1.2 ± 2.6 cm for all athletes of predicted to actual adult height might be statistically significant but is probably not big enough for a significant negative impact on an athlete's sports performance. However, in elite sports small differences in height could still give athletes a competitive edge depending on the event (Simonton, 2017).

Other than the group with all female athletes, every other group with a significant difference has a common denominator: The male combat sport athletes. They have the biggest difference between predicted and actual adult height and the smallest correlation coefficient (r = 0.878). Furthermore, this difference becomes smaller in the other groups when the number of non-male combat sport athletes increases.

The analysis of height difference between medallists and non-medallists of the 2016 Olympic Games of male combat sport athletes revealed a significant difference of 2.0 ± 0.9 cm ($p = 0.034$) between medallists (179.1 ± 11 cm) and non-medallists (177.1 ± 9.5 cm). A smaller mean adult height by 2.6 ± 3.7 cm of male combat sport athletes in this study could potentially negatively influence their (future) sports performance and success. Therefore, this difference is not only statistically significant but could also be a deciding factor at elite levels in sports, since they might not be able to achieve their full height potential that would give them a possible competitive edge over opponents with similar skill levels.

Nevertheless, a taller height might not have the same importance in every combat sport. In Judo, different techniques can be used depending on the athlete's height. Tall athletes usually prefer leg techniques and short and medium-height judokas hand techniques (Lech et al., 2007). Yet, the mean height difference between medallists and non-medallists at the 2016 Olympic Games was 2.0 cm in male combat sport athletes overall and in male judokas only. This indicates that either leg techniques or a greater reach might be beneficial in Judo. Nevertheless, the height difference of predicted and actual adult height in male combat sports athletes should be further analysed as to why this group shows the highest deviation from predictions. Since the TWII/3 method is valid for handball players and female combat sport athletes but not for male combat sport athletes, this could indicate that the height prediction method might not be valid for this group because the growth of these athletes is somehow negatively impacted in the timespan between the recording of the wrist radiograph and the final adult stature measurement.

Growth is a complex process with various influences (Norris, 2022) and remains plastic into adolescence (Thompson, 2022). Therefore, optimal growth can only be achieved if all contributing factors operate in harmony (Mousikou et al., 2023). Possible alterations of this genetic growth potential depend on timing, strength, frequency, duration, and sex, they furthermore primarily affect the endocrine system (Cameron, 2022a). Even though there are several influences on growth, the most probable of such influences during adolescence seems to be nutrition and stress, since many other environmental factors affecting growth can be somewhat ruled out in Austria (Cameron, 2022c; Thompson, 2022).

The growth period during puberty presents a nutritional vulnerability since it is a phase of rapid growth and final adult height can still be negatively impacted (Barker, 2021; A. B. Tanner, 2023). This suppression of growth might be the body's way of conserving energy for essential mechanisms (Christian & Smith, 2018) and can be irreversible without intervention. Even with interventions though, catch-up growth might not always be completely possible (Leroy et al., 2020).

Growth is probably impacted by malnutrition due to several disturbances of the GH-IGF-1 axis. This may include reduced plasma levels of insulin, IGF-1, leptin, and thyroid hormones and increased levels of IGF-binding protein, GH levels and glucocorticoids (Savage, 2013; Thompson, 2022). The secretion of IGF-1 may be directly regulated by amino acids and is therefore sensitive to alterations in the nitrogen balance (Thompson, 2022).

Other than nutrition, stress can also negatively affect growth, as well as metabolism and immune responses during adolescence. If stress persists, the stress response system is chronically activated and might lead to a maladaptation (Charmandari et al., 2003) that inhibits the GH-IGF-1, the gonadal, and the thyroid axis and increases the levels of cortisol. Especially hypercortisolism shows adverse effects in growth (Mousikou et al., 2023). In combat sports, a combination of malnutrition and stress might be possible since chronic stressors affecting growth include malnutrition and intense exercise (Mousikou et al., 2023).

Around 25-80% of young combat sports athletes engage in acute and/or chronic weight loss practices (Berkovich et al., 2016; Viveiros et al., 2015). Acute restrictions that lead to a weight loss of more than 3% of the body mass might have serious negative implications on health status and performance, the most serious being death (Burke et al., 2021). These acute weight loss practices are powerful physiological stressors and might lead to a negative endocrine and metabolic response (Areta et al., 2021). However, it seems that slow recovery is possible when enough energy is available (Areta et al., 2020; Stickler et al., 2019). At the moment it is still unclear whether a longer and small energy reduction, or a short but severe reduction have the same impacts on the endocrine system (Areta et al., 2021).

Repeated bouts of rapid weight loss and chronic negative energy balance might lead to a state of low energy availability, where the body does not have sufficient energy in order to support all functions needed to attain or maintain optimal performance and health (Mountjoy et al., 2018; Wasserfurth et al., 2020). LEA might cause an impaired endocrine system including changes on the thyroid function, disturbances of the hypothalamic-pituitary-gonadal axis, alterations in hormones regulating the appetite, increases in GH resistance, decreases in IGF-1 and insulin, elevated cortisol levels (Allaway et al., 2016; Logue et al., 2020; Loucks & Thuma, 2003; Misra, 2014), and might negatively influence the growth and development of adolescents (Mountjoy et al., 2018).

Furthermore, it is common in combat sports to compete in a weight category below one's natural body weight (V.-P. Boisseau et al., 2005). It has been reported that some adolescent athletes try to stay in a certain weight category that is lower than their natural physiological body weight between competitions for two years or longer, which might negatively impact their growth and development (Berkovich et al., 2016), particularly during their peak height velocity (Berkovich et al., 2016; Mountjoy et al., 2018). Furthermore, absolute energy requirements peak in the late teens, even more so for physically active athletes. Their additional energy requirements put them in danger of chronic LEA (Lakicevic, Reale, et al., 2022), which might decrease their IGF-1 levels, elevate their GH levels, and increase their GH resistance (Fazeli & Klibanski, 2014). Further studies indicate that athletes present with a higher percentage of eating disorders or disordered eating than the non-athlete population, especially athletes in weight-sensitive sports (Vasiliu, 2023).

Studies show that patients with the eating disorder anorexia nervosa have a significantly lower final adult height than anticipated (Misra, 2008; Modan-Moses et al., 2003, 2021; Swenne, 2013). This is associated with very low levels of IGF-1 and a GH resistance as can also be seen in malnutrition (Misra, 2008; Thompson, 2022).

Because of the different age at the pubertal growth spurt in boys and girls, sex specific differences in the loss of the genetic height potential and catch-up growth occur (Downey et al., 2023). Girls with anorexia nervosa showed more severe impairments in growth if they presented the disorder at the age of 13 years or younger or if they were less than 1 year after menarche compared to older girls. These girls might have already gone through their growth spurt with enough energy for normal growth at the onset of anorexia nervosa (Modan-Moses et al., 2012).

In a study on boys with anorexia nervosa, catch-up growth was possible during the first year for those that had not yet started their growth spurt. Boys, who had already initiated their growth spurt, were not able to completely catch-up to the predicted adult height. The loss in height equated to about 4.5 cm of potential height (Downey et al., 2023; Swenne, 2013). Girls with normal growth attain peak height velocity generally at the age of 12 and boys with normal growth at the age of 14 (Soliman et al., 2014). This means, that at the time of usual disorder onset, boys still have more significant growth potential left. Therefore, boys with anorexia nervosa are more likely to have a reduced adult height than girls (Misra, 2008).

In this study, radiographs of the wrist bones for height prediction were obtained from athletes at the age of 14 years. Therefore, at this age the still remaining growth potential is smaller for girls than for boys. This can also be observed in the smaller fluctuation range of height prediction methods for girls than for boys. Hence, it might explain, why only the male and not the female combat sports athletes show a significant difference between the predicted and actual adult height. Even if the female combat sports athletes might have a chronic negative energy balance, it might not affect their growth to the same extent as the boys and might only be observed by other symptoms like amenorrhea (Logue et al., 2020). However, to further investigate this point one would need to retrospectively question these athletes if both male and female athletes actively participated in weight making practices, to what extent they did, and if they showed other symptoms.

Contrary to combat sport athletes, male handball players are not generally known to participate in acute or chronic weight loss practices. Therefore, there's a high probability that they do not have a chronic negative energy balance that could influence their growth. Nonetheless, this does not rule out the possibility of male handballers with eating disorders, disordered eating, or a chronic negative energy balance.

A chronic negative energy balance might however explain the significant difference of actual adult height and predicted adult height of male combat sports athletes. When taking a closer look at the data, 6 of 11 (= 55%) combat sports athletes show a bigger difference to predicted height than the method's fluctuation range indicates, but only 2 of 12 (= 17%) male handball player's predictions are outside this range. In general, the actual adult height of 18 of the 45 analysed athletes (= 40%) was not within the fluctuation range (see table 9). Of those 6 male combat sports athletes, 4 have a difference of -4.4 cm or bigger. One even had a height difference of -9.2 cm, which puts him outside the line of agreement as seen in the Bland-Altman plot (figure 10). In the study by Swenne (2013) a loss of about 4.5 cm of potential height was observed in boys with anorexia nervosa. This indicates that eating behaviours of male combat sport athletes show similar effects on their growth than the eating disorder anorexia nervosa had on the height of these boys.

Yet, growth can be affected by several factors. Thus, other or additional influences on their growth should be considered, including endocrine growth disorders, pollutants or infections (Cameron, 2022b; Schell & Rousham, 2022). However, growth disorders are far less common than eating disorders or disordered eating in athletes (Bratland-Sanda & Sundgot-Borgen, 2013; Murray et al., 2016; Rona & Tanner, 1977) and might therefore only play a role for a small number of athletes. Furthermore, height prediction might vary between different ethnicities (Ostojic, 2013). Since the study data is anonymised, other ethnicities of some athletes cannot be ruled out. Endocrine growth disorders or a different ethnicity might also explain the adult height of an athlete with a 5.1 cm greater than predicted height. However, overnutrition or obesity might also cause the taller height (Urakami, 2020). This deviation even lies outside the line of agreement in the Bland-Altman plot.

When taking another close look at individual data of the athletes, it was not just male combat sports athletes that had such a big difference between predicted and actual adult height. 2 female handball players seem to have had a big negative influence on their height as well, since one is smaller by 4.2 cm and one by 5.5 cm compared to their predicted height. These great differences between predicted and actual adult height suggest a similar influence on growth as in the male combat sports athletes. Which might indicate that they had a chronic negative energy balance as well. These findings also fit the results of recent studies with female handball players (Castillo et al., 2022; Miralles-Amorós, Vicente-Martínez, et al., 2023; Mora-Fernandez et al., 2022). In these studies, researchers observed a high prevalence of low energy intake in the sport, with some athletes even exhibiting signs of eating disorders (Mora-Fernandez et al., 2022). Additional information on eating habits and maturation status of the 2 female handball players could help identify as to why their adult height deviated that far from their height predictions.

Since eating disorders, disordered eating, or LEA might lead to additional severe health problems other than a possible negative influence on growth (Mountjoy et al., 2018), athletes might benefit from an implementation of screening tools to detect eating disorders or disordered eating. The data suggests that especially adolescent males in a weight sensitive sport have a high risk to develop eating disorders or disordered eating. Furthermore, athletes in general seem to present with a higher percentage of eating disorders or disordered eating than the non-athlete population (Vasiliu, 2023). Therefore, validated screening instruments for eating disorders (Fairburn, 2008), LEA (Melin et al., 2014), Relative Energy Deficiency in Sport (REDs) (Mountjoy et al., 2023) or an Anthropometric, Biochemical, Clinical, Dietary, and Environmental (ABCDE) Assessment should be used to evaluate the health of youth athletes (Sundgot-Borgen et al., 2013). The biochemical assessment includes the measurement of cortisol. Since hypercortisolism due to chronic stress shows adverse effects in growth, this blood parameter might be an early indicator for such a negative influence (Mousikou et al., 2023). This biochemical assessment could be further expanded by the measurement of IGF-1 levels in the blood as another early indicator for negative growth influences (Johannsson et al., 2018).

However, other than screening instruments for eating disorders, REDs or LEA, these blood parameters might not be able to differentiate between chronic stress or a chronic negative energy balance because malnutrition acts as a chronic stressor itself (Mousikou et al., 2023). Since growth can be altered by various influences (Norris, 2022) it might be very difficult in general to trace negative differences between predicted and actual adult height to a singular or to a specific influence. Further research that can help eliminate some of the variables impacting growth would be needed. These differential diagnoses could include

GH deficiency, chronic diseases, long-term drug use (for example anabolic steroids, opioids, glucocorticosteroids), congenital or acquired hypogonadotropic hypogonadism, genetic defects or hyperprolactinaemia (Mountjoy et al., 2023).

Moreover, especially in the group of male combat sports athletes, additional research would be needed to help identify if negative influences on growth during adolescence stem from repeated bouts of rapid weight loss and the stress this induces (Barley et al., 2019), from a chronic negative energy balance or from other factors (Mountjoy et al., 2018). What makes it less likely for making weight itself to negatively influence growth however is the fact that it seems to be possible during phases of sufficient energy intake to catch-up growth, even though the factors that allow catch-up growth are not clearly understood (Neale et al., 2020; Prentice et al., 2013). Additionally, the long-term effects of rapid weight loss are not well studied (Lakicevic, Matthews, et al., 2022). So far, it is linked to eating disorders, higher levels of obesity after retirement and to endocrine dysfunction and kidney damage (Burke et al., 2021). Further studies are needed to provide evidence on the impact of repeated weight cycling bouts on growth.

The intergroup comparisons using an independent sample t-test or ANOVA found no significant discrepancy in the difference of predicted height minus actual adult height between any group. This indicates that there might have been a similar measurement error or other systematic errors in all groups and that the difference between groups is not big enough to be significant in this small sample size. The Tanner-Whitehouse methods and other manual height prediction methods are known to result in systematic deviations (Blum et al., 2022). A small sample size further leads to a very low power for all these comparisons. Therefore, these results should be interpreted with caution (Durlak, 2009). The calculations of hedge's g showed almost no effect ($g = 0.05$) between the female handball players and the female combat sports athletes since the mean difference between predicted height and adult height and the mean standard deviation are almost identical for both groups. Yet, a medium to large effect size ($g = -0,65$) was found for the comparison of male handball players and male combat sports athletes. The effect size of the intergroup comparisons becomes smaller with an increasing number of non-male combat sport athletes. Same as with the results from the *t*-test for paired samples this indicates that the male combat sports athletes are the group deviating the most from other groups. Especially the differences between the male combat sport athletes and the male handball players should be further analysed to determine possible reasons for the deviations from the predicted height minus the actual adult height between these two groups, since a medium to large effect size should not be ignored even if it is not statistically significant. Other than combat sports, handball is not considered to be a weight sensitive sport, therefore this medium to large effect size could as well be explained by differences in caloric intake of those two groups. For firm evidence however, further studies under standardised conditions are needed.

There are several limitations in this study that should be addressed. A significant limitation is the small sample size and the therefore resulting small statistical power. Another drawback is the high inter- and intra-rater variability of manual height prediction methods (Prokop-Piotrkowska et al., 2021) and that systematic errors cannot be ruled out as well. Additionally, it is not known whether the measurements were all analysed by the same person, or several others and it is not clear which height prediction method (the TWII or the TW3) was used for which athlete. Since Leistungssport Austria now uses the BoneXpert method, limitation of high inter- and intra-rater variability could now be ruled out. Therefore, a comparison of this study's results with new data, analysed using the BoneXpert method, might rule out or confirm an inter- and intra-rater variability in this study. Additionally, if the BoneXpert method underestimates the final adult height as well, it might indicate that this deviation could stem from secular trends in the study population.

Furthermore, this was a retrospective and anonymised study. Therefore, additional athlete information was missing and could not be factored into the discussion and analysis. There is for example no data available on the ethnicity of the participants, but it is believed that most of the athletes were Caucasian of Central European descent. However, a greater diversity and a different ethnic background of the athletes cannot be ruled out.

Additionally, there is no information about dietary intake, energy expenditure, or weight of the athletes. Consequently, the suggested influence of a negative energy availability on growth is based on speculation since combat sports athletes are known to participate in some kind of regular weight manipulation. Yet, there is no data available whether the combat sports athletes actually participated in rapid weight loss practices and if so, for how long and to what extent. It is also not known in what weight category they participated in competitions. Further, it might be interesting to see if athletes in certain weight categories or with a lower body mass index (BMI) are more likely to exhibit negative influences on their growth or health. So far, it is unclear if RWL or LEA shows a different effect in individuals if their body composition differs since energy stores might provide protection against negative endocrine responses (Areta et al., 2021).

Another important missing piece of information is the exact athlete age when the radiographs of the wrist bones were obtained and the age of the final adult height measurement. In a study by Prentice et al. (2013) catch-up growth was possible until the age of 20-23 years. Therefore, it might be plausible that some of these athletes were able to catch-up in growth and subsequently achieved an actual taller adult height. Additionally, it might be helpful for the interpretation of the results to know whether the athletes had already initiated their growth spurt at the time the wrist radiographs were obtained. Adolescents who already reached their peak height velocity might have already gone through their growth spurt with enough energy for normal growth and might have less growth potential left that still could be negatively influenced (Misra, 2008; Modan-Moses et al., 2012).

Another limitation is that growth can be influenced by various factors which cannot be ruled out in this study. For firm evidence, on why the growth of male combat sports athletes is negatively influenced, studies under standardised conditions are needed that can rule out several such factors. However, especially studies on the long-term effects of LEA and RWL are very difficult to achieve under standardised conditions. For one, these studies are resource-intensive for the researchers and the participants, since a strict control of dietary intake, energy availability and sample collection is needed. There are even several limitations when it comes to the assessment of the energy expenditure and energy intake, especially in the field (Burke et al., 2018; Heikura et al., 2018). For another, the ethic perspective needs to be considered since long-term exposure to LEA or RWL might lead to irreversible health consequences. Moreover, it is unclear if a chronic but less severe energy reduction has the same effect as a short but very low energy availability and if an energy surplus can compensate for a such a deficiency (Areta et al., 2021).

5 Conclusions and Outlook

In conclusion, the data shows that the used height prediction methods are not valid for all analysed athlete groups. They are valid for all handball players and for female combat sports athletes but not for all female athletes and not for any group that includes male combat sports athletes. In case of the female athletes the small difference of the predicted and actual adult height (-0.9 ± 1.9 cm, $p = 0.032$) does not seem to be a deciding factor for (future) success in sports performances and might just show a significant difference due to the small sample size of the study group.

However, the predicted adult height of male combat sports athletes differs significantly from their actual adult height and might therefore be a deciding factor at elite levels in sports since they might not achieve their full height potential that would give them a competitive edge. The smaller actual adult height of the combat sports athletes indicates some negative influence on their growth between the recording of the wrist radiograph and the final adult stature measurement.

Since growth can be influenced by various factors, it is difficult to pinpoint a specific reason for this negative influence on the athlete's growth. Nevertheless, weight sport athletes are known to regularly participate in rapid weight loss practices and to restrict their caloric intake. Therefore, it seems probable that some form of caloric restriction might have a negative impact on their growth. Furthermore, a not significant but medium to large effect size was found for the comparison of male handball players and male combat sports athletes, which further indicates different influences on growth in these two groups. Other than combat sports, handball is not considered to be a weight sensitive sport, consequently, the effect size could as well be explained by differences in the caloric intake of those two groups.

For firm evidence however, studies under standardised conditions are needed. These future studies should include data on dietary intake, energy availability, analysis of blood parameters, body weight and BMI of athletes, the weight category they compete in, as well as the frequency and extent of rapid weight loss practices. Since studies investigating the long-term effects of LEA or RWL might lead to irreversible health consequences, they are difficult to justify from an ethical perspective. Nevertheless, it would be important to have a closer look at the eating habits of young athletes and their blood parameters, especially if they are part of youth athlete development programmes, for early detection and intervention of eating disorders or disordered eating, and other negative influences on their health like stunting since not only male combat sports athletes might be at risk.

Other than the implementation of screening tools and studies under standardised conditions, there probably should be further rule changes in combat sports to complicate the participation in possibly harmful rapid weight loss practices, especially in youth competitions. Finally, athletes, coaches and parents should be educated about the possible health consequences of RWL and LEA.

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