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Developmental changes in the youth athlete: implications for movement, skills acquisition, performance and injuries.

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This narrative review summarizes the current literature on early sport specialization and changes that occur in the musculoskeletal system throughout growth and maturation. It discusses the impact of development on the motor and sensory systems and how this contributes to movement and coordination in the young athlete. With the increasing number of youth athletes in organized sport and the popularization of early sport specialization, the purpose of this paper is to educate those involved with the youth and adolescent athlete to important changes that are occurring at this time in development and the implications they have on movement, performance and injury. It is important for coaches, parents and athletes to understand and acknowledge the changes that are occurring, and to expect some difficulty in adaptation, which may be evident as either a plateau or deterioration in performance, or typical overuse injuries that are seen in the adolescent athlete.

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Cet article de synthèse résume la littérature actuelle sur la spécialisation sportive précoce et les changements qui se produisent dans le système musculo-squelettique durant la croissance et la maturation. Il traite des effets du développement sur les systèmes sensoriels et moteurs et comment ces systèmes participent au mouvement et à la coordination chez le jeune athlète. Le nombre de jeunes athlètes dans les sports organisés est à la hausse et la spécialisation sportive précoce est la mode. Cet article vise à sensibiliser les personnes travaillant auprès des jeunes et des adolescents athlètes aux importants changements se produisant au cours du développement et aux répercussions sur le mouvement, la performance et les blessures. Il est important que les entraîneurs, les parents et les athlètes comprennent et reconnaissent ces changements et s'attendent à certaines difficultés d'adaptation, qui peuvent être signe d'un plateau ou d'une détérioration de performance, ou alors des blessures de surmenage caractéristiques observées chez l'athlète adolescent.

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MOTS CLÉS : chiropratique, pédiatrie, athlète, croissance, développement

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Introduction

In 2008, there were 60 million participants between the ages of six and 18 years old in organized sport in the United States, compared to 52 million, eight years prior.[1] The number of youth participating in competitive sports is steadily rising with a concurrent drop in school-based physical education programs; only 29% of youth participate in daily classes.[1] This results in a large number of competitive athletes lacking exposure to different sports, and for children who do not participate in competitive sports, an overall lack of physical activity.[1] Discussions surrounding early sport specialization (ESS) run rampant in media and sport communities alike. ESS is defined as intensive year-round training in a single sport at the exclusion of other sports.[2] It has gained traction with the belief that ESS is essential for future sport success.[2] A recent cross-sectional study of club team athletes between 12 and 18 years old found that approximately 91% of athletes believed that specialization in one sport increased their chances of improving in that sport.[3] Sixty-six and 81% thought it would increase their chance of making college or high school teams, respectively, with only 45% believing it increased their risk of injury.[3] ESS can also arise from peer, coach or parental pressure, where up to 75% of athletes report being influenced by one of these factors.[2]

The ESS literature stratifies athletes by degree of specialization, based on three criteria: 1) training more than 8 months per year, 2) choosing a single main sport, 3) quitting all sports to focus on one sport.[2,4,5] The degree of specialization increases with a greater number of criteria applying to the athlete in question: low (1/3), moderate (2/3) or high (3/3).[2,4,5] The risk of injury also changes accordingly. Athletes with low specialization have low risk of injury but moderate risk of acute injury.[2,4,5] Moderately and highly specialized athletes have moderate and high risk of injury, respectively, and a low risk of acute injuries.[2,4,5] It is important to note that the criteria regarding the degree of specialization does not take into account athletes who have only ever played one sport. In this case, they cannot answer 'yes' for the third criteria but may still be considered a highly specialized athlete.[2,4,5] There is evidence to suggest that there is an increased prevalence of certain injuries associated with ESS, such as patellofemoral pain, Osgood-Schlatter disease and patellar tendinopathy.[4,6,7] Participating in over 16 hours per week of organized activity, regardless of the number of sports, is also associated with an increased risk of injury.[2,4]

Sport and recreation account for 8.6 million injuries in the emergency room every year.[8] Males between five to 24 years old account for over 50% of these injuries.[8] Basketball, football and soccer are in the top five activities resulting in injuries in people under the age of 18.[9] Injuries in these sports follow a similar pattern, where they peak around 14-16 years old, and decline significantly thereafter.[9] Injuries reported from a sports medicine clinic report that 67% of injuries were to the lower extremity (foot and ankle 22%, knee 13%, hip and groin 10%).[10] Serious overuse injuries were more commonly of the knee (34%) and serious acute injuries were more commonly of the foot and ankle (22%).[10] Unfortunately, details regarding sport activities of these athletes were limited.

ESS has been popularized by Malcolm Gladwell's book, Outliers, where he discusses the 10, 000-hour rule proposed by Ericsson in 1993.[5,11–13] Ericsson identifies the importance of deliberate practice, a highly structured practice environment explicitly used to improve performance, that is inherently not enjoyable.[5,11–13] He originally proposed this theory based on a small number of chess champions, elite musicians and mathematicians, however there is limited evidence that this applies to athletes.[5,11–13] The proposed risks of ESS include a greater risk of injury, not finding their favourite sport as a result of decreased sport sampling, limiting overall motor skill development and limiting sociological and psychological development due to isolation, staleness and burnout.[5,11] In addition, it has been identified that success at a young age does not predict long-term success in a sport, and in some cases may limit elite level achievement.[2,5] For example, in swimming, ESS resulted in less time on the national team and early retirement compared to those who did not specialize as early.[2,5] In a cross-sectional study comparing age of specialization in high school, collegiate and professional athletes of various sports, it was identified that high school athletes specialized on average two years earlier than collegiate and professional athletes.[14] In contrast, the benefits of early diversification include augmenting physical and cognitive skills, transfer of similar elements between sports (movement, perceptual and conceptual), and the positive effects of cross-training.[11]

Therefore, recommendations surrounding specialization in sport include sport sampling at a young age, participating in less hours of sport per week than their age while always remaining below 16 hours of total activity per week, and if ESS is chosen, to include an integrative neuromuscular program.[5,7] The recommended age of specialization varies based on sport. Early entry sports such as gymnastics, diving and figure skating typically require specialization in early adolescence.[5,7] Team sports, tennis and golf are recommended to specialize in middle adolescence, and endurance sports and track and field can specialize in late adolescence.[5,7]

When managing the adolescent athlete, training and competition requirements and scheduling are important concerns, however, the impact of physical and physiological changes cannot be ignored. With the increasing number of youth athletes in organized sport and the expectation of success and pressure from peers, parents and coaches, the purpose of this paper is to educate those involved with the youth and adolescent athlete to important changes that are occurring at this time in development and the implications they have on movement, performance and injury.

Growth, Maturation and Development

The use of the word development can be used in broad concepts of change in biology, behaviour and psychology.[15] Growth refers to the increase in size of the body or its parts, measured by stature, body mass or composition.[15] Maturation refers to the tempo and timing of progress towards a mature biologic state.[15] It can be measured by secondary sex characteristics, skeletal maturation and age at peak height growth.[15] The difficulty in measuring maturation stems from the varying rates of progress towards the same end point, limitations of measures representative of maturation and that chronological age is a poor marker of maturity status.[15]

Bone growth

As a child grows, they accrue more bone mineral mass and less cartilage due to physeal closure.[15,16] Accrual of bone mineral density (BMD) can be promoted by increased physical activity and reduced by excessive adiposity.[17–20] Average age of peak height velocity (PHV) is 12 years old in girls and 14 years old in boys.[21] The mean growth for children prior to the growth spurt is six cm/year and can increase to nine cm/year in girls and 10 cm/year in boys.[15,22,23] This rate of growth can last two to three years.[22] There is also differential growth between the legs and trunk, where leg growth precedes growth of the trunk in most youth.[22] Peak leg length growth occurs prior to or during PHV in 75.6% of girls and 77.6% of boys.[24] Peak trunk height growth occurs during or after PHV in 71.3% of girls and 83.5% of boys.[24] Therefore, leg length to trunk height ratio increases four years prior to PHV, reaches a maximum at PHV and subsequently decreases for three years thereafter.[24] This should be a consideration when using body stature or height to estimate strength differences, as many muscles cross both the legs and trunk, and global measures may not adequately represent the length of the legs during these times.[15,25] It may also be used as an estimate for maturation if athletes can be tracked over time.

Muscle growth

Peak growth velocity of body mass occurs approximately one year after PHV.[26] In girls, this tends to be fat mass, and in boys, muscle mass.[15,16] The delay in body mass development results in deferral of muscle length and mass relative to bone growth and size.[27–30] The increase in bone growth results in greater limb inertia, requiring more strength of the muscles to control the limb,[31,32] and a greater demand of muscles that are not fully developed.[33] When assessing a 14-year old's capacity to maintain knee extension in a seated position, it requires 4.7 times the torque than it does at six years old.[33] Muscle length is stimulated by the growth of the bone, where sarcomeres are added in series at the musculotendinous junction and optimal fiber length remains relatively constant.[16,27,34,35] In addition, changes in pennation angle occur contributing to increased muscle stiffness and subsequent increases in strength.[36–39] While the majority of strength improvement throughout adolescence is due to the increase in muscle size and mass, these changes can also affect the moment arm of the muscles around the axis of rotation of a joint.[40,41] Specifically, the Achilles and patellar tendon moment arms are smaller in prepubescent children.[42–44] Increases in moment arm with growth may manifest itself as an increase in strength, as it provides a more efficient mechanical advantage to the muscle.[41,43]

Tendon growth

Tendon length and cross-sectional area (CSA) increase by approximately 53% and 93%, respectively, throughout development.[39] Increases in collagen fibril diameter, density and intra-fibrillary cross-linking change the Young's modulus of the tendon, which can also be affected by increased loading of the tendon that occurs throughout maturation.[39] It is well known that musculoskeletal stiffness changes with high-intensity loading and unloading in adults.[45–49] Resistance training increases musculotendinous stiffness, whereas unloading decreases stiffness.[45–49] In prepubertal children, one study identifies similar results with a 35% increase in Achilles tendon stiffness after 10 weeks of resistance training, with no change in the control group.[50] The impact of tendon length and CSA changes throughout development have not yet been investigated.

Role of fascia

Fascia is defined as the soft tissue component of the connective tissue system that permeates the human body; it is part of the body's force transmission system that adapts its fiber arrangement and density according to local tensional demands.[51] The superficial fascia is formed by many different layers with the primary purpose of sliding one layer over the other.[52] These layers communicate through a microvacuolar system, a highly deformable web in several directions with vessels and nerves.[52] The deep fascia is the last layer before reaching structures such as muscles and bones.[52] It has a well-developed vascular and lymphatic system, various types of proprioceptive receptors, myofibroblasts and innervation from the autonomic sympathetic system.[52] This fascial system is crucial for the transmission of muscle force and correct motor coordination, for example, it can control the orientation of muscle fibers to better reflect force direction for a task.[52] Fascia develops in response to load which will be the primary factor in determining its changes throughout development, for example, the iliotibial band becomes strong and fibrous in response to bipedal locomotion, whereas it does not develop into as strong a structure in those who are wheelchair-bound.[52] In fetal and neonate feet, there is a continuous heavy layer of collagen wrapping from the Achilles tendon around the calcaneus to the plantar fascia.[53] Only a superficial layer remains and becomes part of the calcaneal periosteum by mid-20 years old, and no longer remains continuous through the periosteum in the elderly.[53] It appears that there are fascial changes that occur throughout development, however no further investigations have been conducted to describe them.

Sensory development

Some evidence suggests that humans are born with a precocial sensory system, meaning that all sensory systems are developed to varying degrees at birth.[54–56] It is also suggested that newborns are able to integrate different sensory modalities.[57,58] When challenged with a postural disturbance, children and adults show similar feedback processes; however, feedforward mechanisms are less developed in children.[59,60] Feedback control is the modification of movement in response to information from the sensory system that arises during the movement.[61] In contrast, feedforward movements are made without the use of sensory feedback during the action, therefore requires an internal map for accuracy of performing a movement.[61] Feedforward control and anticipatory contraction during movement depends on the ability to control inertial forces.[62–64] Therefore, the ability to control the growing skeleton will contribute to the development and limitation of feedforward mechanisms in this age group. By 11 to 13 years old, adolescents can choose between feedforward and feedback mechanisms; however, they still demonstrate a decreased ability to plan movement, particularly with greater task constraints.[60,65–70] Children also have more difficulty with conflicting cues, such as differences in vestibular and visual feedback.[59,60,65] In order to refine postural control, humans require the ability to reweight sensory information appropriately.[59,60,65,71] The ability of children to appropriately and quickly reweight sensory information during a task increases with age.[65,71]

Implications for Movement

When a task is performed appropriately, it reflects the interaction between the neuromuscular and sensory systems providing adequate movement planning, execution, and adaptation based on afferent feedback. With so many changes occurring throughout development, it is not difficult to imagine how they might affect movement and performance.

The development of muscle synergies begin in the legs and trunk becoming apparent around seven to nine months old, and continue until approximately 10 years old.[72,73] The patterns that arise are variable and display greater co-contraction to stabilize the joints.[72] The primary limiting factor for the emergence of appropriate muscle synergies in multi-joint action, including independent stance, is the development of anthropometric characteristics, such as mass and inertia, and the ability to generate sufficient force and joint stability to support the body against gravity.[63,64,74] In addition, difficulties in task optimization may result due to the lack of full utilization of passive structures in the development of multi-joint movement, as is needed in the stretch-shortening cycle (SSC).[75] The SSC is an eccentric stretching action prior to a subsequent concentric shortening of a muscle in the production of a movement.[39] The stretching action leads to a pre-load of a muscle, contributing to an enhanced performance of the concentric movement.[39] At 11 years old, adolescents act as a simple spring mass, taking advantage of the potential elastic energy stored in their muscles and tendons.[76,77] With age and practice, the efficiency of this system improves, for example, they learn to run more efficiently, finding their preferred stride frequency.[77–80]

A number of factors, including the continued development of contractile properties of the muscle, lower neuromuscular efficiency, musculotendinous stiffness and greater electromechanical delay (EMD) contribute to a lower voluntary muscle activation in children.[41,46,81–84] EMD represents the time between muscle activation and force production, and it continues to decrease up to 10 years old.[39,67] EMD can also be affected by muscle and tendon stiffness, neuromuscular development, and muscle relaxation time.[39,85,86] Children have a greater EMD, therefore it takes them longer for movement to occur after muscle activation begins. As these factors change throughout development, so does the ability of the child to fully activate muscles, take advantage of the SSC and produce more rapid and coordinated movements.

Joint and limb stiffness is controlled by muscle and tendon stiffness rather than passive structures crossing the joint.[87] Therefore, an increase in agonist and antagonist muscle contraction will lead to greater joint stability.[87] This suggests the importance of considering the contribution of agonist and antagonist muscles to movements, as joint movement output will be as a result of the balance between their contraction throughout a movement.[40] Failure to consider the antagonist, will underestimate the contribution of the agonist.[40,88] When assessing single joint force production and movement, co-activation varies based on the joint and the movements being performed.[40] In pubertal children, antagonist activation is comparable to those of adults when examining a single joint movement, but differences arise in more dynamic and complex tasks such as walking, where co-activation decreases with age.[41,89–92]

In the pediatric population, the emergence of multi-joint complex movements occurs as a result of the interaction of task requirements, environmental constraints and the developing nervous and musculoskeletal systems.[93] With regards to the learning of a new task, there are three principles that need to be considered: 1) controlling body mass, 2) opposing and taking advantage of gravity when appropriate, and 3) matching muscular and non-muscular forces efficiently (taking advantage of the SSC).[94] When infants learn a new task, they begin by freezing their mechanical degrees of freedom in order to achieve the task at hand.[95] As learning continues, they release them in order to use various ways of achieving the same task, allowing a more adaptable response to perturbations.[96] When assessing adaptations to walking after a perturbation, it is evident that temporal and spatial adaptations do not develop at the same speed.[97–99] In a study with a split treadmill, different speeds were provided for the left and right legs.[99] Children as young as three years old, were able to adapt to a change in treadmill speed by changing stride frequency (temporal adaptation), however, stride length (spatial adaptation) was only used after approximately 12 years of age.[99] Thus, if using adaptive strategies as part of the rehabilitative process, children under 12 years old should be given more time for training than adults.[99]

Implications for Skills Acquisition

All object projection skills (throwing, striking and kicking) integrate the generation and transfer of linear and rotational energy with an open kinetic chain.[100] They require the effective use of segmental inertial characteristics and exploitation of elastic tissue characteristics.[100] The generation of force in the open kinetic chain occurs due to proximal-to-distal sequencing of segments where the distal segments move relative to the proximal segment and add torque to the movement as the proximal segment begins to slow down.[101] This takes advantage of the segment mass and the elastic tissues across the joint to transfer and add torque to a movement.[101] The stretching of tissues across the joint promotes greater muscle activation and enhances the voluntary force contribution to the movement.[102,103] Optimizing the timing of this sequencing allows for greater recovery of stored elastic potential, there-by reducing joint torques and improving the outcome of the movement.[102,104]

The development of overarm throwing and striking are quite similar, differing only in the position of the arm to accomplish these tasks and whether the athlete uses equipment (ie. racquet).[100,105,106] As the advancement of this skill occurs, there is greater involvement of the trunk and lower limbs contributing force generation.[107–109] In addition, there is greater use of upper extremity lag to take advantage of the passive tissue stretch and greater recruitment of associated muscles.[105,106] Those who are less advanced or effective at these skills do not effectively exploit the advantage of the SSC.[107–109] It appears that there are one or more constraints that acts to systematically delay the development of striking compared to overarm throwing, Therefore, teaching both of these skills simultaneously may have a crossover effect.[105]

The development of kicking is different than throwing and striking as special considerations for the lower limb include the approach step, range of motion of the hip, trunk and arms and dynamic balance.[100] When learning of kicking begins, it is done from a static position where the kicking leg is swung back and moves forward to hit the ball, often limited by static balance.[100,110] As development of this skill progresses, it becomes more dynamic where the approach step is preceded by a run or jump, limited by dynamic balance abilities.[100,111] Range of motion requirements are similar to throwing and striking, where greater use of available range of motion leads to a greater speed of the object due to more efficient use of passive structures across joints.[110]

Given how learning occurs, even as infants, it is important to focus on the functional outcome of a task, rather than instructional cues on how to perform it.[112] Focusing on a functional outcome provides the learner with the opportunity to explore movement and the optimal method of performing a task for their own preferred efficiency.[101] In addition, changing environmental constraints can facilitate the learning of different movement outcomes while keeping the task consistent.[100] With regards to teaching object projection skills, focusing first on promoting the use of the kinetic chain is likely beneficial, and can be done by asking the athlete to focus on throwing or kicking with maximum velocity.[112,113] The use of this focus is more likely to produce a distal temporal lag, thus promoting the use of the SSC.[113] Once the athlete has reached intermediate levels of developmental sequencing, accuracy constraints can be added to further improve completion of the task.[113]

Implications for Performance

With regards to performance, it can easily be inferred how developmental changes contribute to differences within and between players. With maturation, changes in body size, muscle mass, and neuromuscular systems contribute to the potential for greater physical outcomes. When considering the stiffness of the muscle and tendon tissues placed in series, greater potential elastic energy will be primarily stored in the more compliant tissue.[87] Therefore, the changes in these structures will contribute to the performance of movements requiring the use of the SSC.[47,84] In addition, the changes in stiffness will have an impact on the sensory feedback, where lower tendon and muscle stiffness will result in less afferent feedback from receptors.[87,114] This has implications on movement, coordination and performance as a result of feedback control processes. The increase in muscle-tendon stiffness associated with development improves power production during multi-joint tasks, reaching adult levels by late adolescence (16 to 18 years old), this is further improved by changes in EMD and rate of force development.[76,86,115]

While there is the potential for improved performance, considerations should be made for athletes in their growth spurt, as the rapid growth of bone, and delay of muscle growth leads to a relative lengthening and an increase in resting tension of the muscles. In addition, the increased mass of their segments, and delay in muscle mass development limits the amount of force the muscles can produce to move the heavier segments. This also has implications for sensory feedback of the muscles and joints, affecting the neuromuscular control of simple and complex movements as demonstrated by impairment of coordination, or the classic "adolescent awkwardness", immediately during and up to one year following their rapid growth.[87,116–119] It is not unusual to expect a plateau or deterioration of performance while the athlete adapts to perceptual, spatial, physiological and biomechanical changes that are caused by growth.[40] In considering the difference in development between boys and girls, early maturing boys tend to have the athletic advantage as they experience greater shoulder width and muscle mass development, compared to girls who tend to gain hip width and fat mass.[15] Therefore, late maturing girls tend to have the athletic advantage, demonstrating more linear physiques and less fat mass.[15]

Implications for Injury

The changes occurring throughout development also place considerable risk for certain injuries. Lag of muscle hypertrophy and length are important training considerations during the growth spurt and one year thereafter.[120,121] Peak BMD occurs approximately one year after PHV, therefore bones have lower energy and force absorption compared to adults.[122,123] In addition, soft tissues changes may also lead to poor control of impact forces across joints, strength imbalances and uncoordinated biomechanics.[124] With the added stress of greater resting muscle tension after the growth spurt, it may not come as a surprise that growth-related injuries are common in athletes of this age, such as traction apophysitis'.[33,125] Although there is a lack of epidemiological data to support this, this is often supported anecdotally.

Any increase in training around this time could increase injury susceptibility.[126] Improvements in skill through developmental sequencing, can reduce the joint torques and improve object projection speed by improving mechanical efficiency.[102,104] However, implications of sport equipment and personal protective equipment must be considered, as inappropriate use may add additional overload to the athlete or lead to negative impact absorption or energy transfer.[124] For example, the use of tennis racquet, may increase the stress on the musculoskeletal system by increasing the moment arm of ball forces.[105,106]

Finally, considering maturation is an important aspect of injury prevention, as this varies between individual athletes. This has significant implications in contact sports where teams are formed by age-group. For example, a study of ice hockey players between 13 and 15 years old found that body mass and stature differences between the smallest and largest players were 53 kg and 53 cm, respectively.[127] When determining force impact differences between them, this resulted in a 357% difference.[128]

Conclusion

There are many changes occurring in the developing athlete. The growth spurt, or PHV, is an indication of the greatest period of growth, where growth rates can double those prior to that time. This results in a relative overload of the muscle and fascia, which is delayed in both length and CSA growth compared to bone, and a heavier segment but no concurrent improvement in strength to control it. It is currently unknown what changes occur in the fascial system during development and the impact this has on movement or motor control. The year following PHV is a year of system adaptation[129], which sees increases in muscle length and CSA, muscle and tendon stiffness, and BMD. This sequence of change has major implications for the coordination of movement which tends to deteriorate around the time of the growth spurt, or shortly after. In addition, with the advent of ESS and an increasing prevalence of year-round participation in competitive sports, it is important to consider this information to inform training, competition and performance decisions for these athletes. Coaches, parents and athletes must understand and acknowledge the changes that are occurring around this time, and expect some difficulty in adaptation, which may show itself as either a plateau or deterioration in performance, or typical overuse injuries that are seen in the adolescent athlete. The physical body of the athlete is already under considerable stress as a result of growth, and therefore may be susceptible to injuries. As a coach and parent, considerations may include reducing the training volume or intensity, spending more time on skills acquisition as well as ensuring sport equipment is reasonable for the state of the athlete particularly during the time of PHV.

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