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A Systematic Review of Sensorimotor Function during Adolescence: A Developmental Stage of Increased Motor Awkwardness?

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ABSTRACT

Background Although adolescent motor awkwardness and increased injury susceptibility have often been speculated and researched, studies regarding adolescent regressions in motor control have yielded inconsistent conclusions. Thus, the relationship between adolescent maturation and injury risk remains unclear. The purpose of this study was to systematically review the literature relative to two questions: (1) Which sensorimotor mechanisms are not fully mature by the time children reach adolescence? and (2) Is adolescence a period when children exhibit delays or regressions in sensorimotor mechanisms?

Methods Systematic searches for keywords were performed in February 2010 using PubMed MEDLINE (from 1966), CINAHL (from 1982) and SPORTDiscus (from 1985) databases. Articles were reviewed relative to predetermined criteria, and the methodological quality of each included study was assessed.

Results The search identified 2304 studies, of which 33 studies met the inclusion criteria. All 33 identified studies provided results associated with Question 1, 6 of which also yielded results pertaining to Question 2. The search results indicated that many aspects of sensorimotor function continue to mature throughout adolescence, and at least some children experience delays or regressions in at least some sensorimotor mechanisms. The results also exposed several significant weaknesses in our knowledge base.

Conclusion The identified knowledge gaps are critical barriers because they hinder methods for identifying children at high risk and diminish the efficacy of targeted prevention programmes. Implications regarding research on adolescent injury risk are discussed and recommendations for future research such as improved methodological designs and integration of non-linear analyses are provided.

INTRODUCTION

High rates of injury incidence related to sports and recreation in children aged 10–14 years (an estimated 5387.3 per 100 000 population) identify adolescence as a potential period of childhood development in which children may be at an amplified risk for such injuries.[1] There is some evidence that indicates that the timing of increased injury risk may coincide with the adolescent growth spurt.[2 3] Injuries at this age can devastate a child's ability to participate in physical activities and may trigger long-term sequelae such as early onset of osteoarthritis.[4 5] Regular participation in physical activity improves strength, prevents obesity and increases self-esteem.[6] Moreover, adolescent activity levels can profoundly affect a child's future health and well-being.[7] In order to minimise healthcare costs and optimally assist children in becoming healthy, active adults, efforts must be made to identify factors that increase sports- and recreation-related injury susceptibility during adolescence and to devise and implement prevention programmes to target modifiable risk factors.

Although a number of studies have considered such factors as body size, fitness and previous injury relative to injury risk, there is presently a paucity of evidence that identifies modifiable risk factors for injuries in youth sports.[2] One area that has often been discussed but rarely tested with regard to increased injury risk is that of 'adolescent awkwardness'. Delays or regressions in sensorimotor function relative to rapid growth spurts offer appealing explanations for increased injury susceptibility during adolescence. For example, the incidence in distal radius fractures in children is at its highest at the same period of development when children undergo a rapid growth spurt during puberty.[8] However, studies that have investigated adolescent deficits in motor control and skills have been inconsistent in their findings and conclusions[9–12] and no current consensus on the presence or absence of regressions in motor control during adolescence currently exists.

Incongruities in study methods may account for some of the inconsistencies in study results.[13 14] Discrepancies may also relate to the use of global representations of sensorimotor function (eg, motor skill performances) instead of measurements of specific mechanisms of sensorimotor function (eg, sensory integration, neurocognitive processing and neuromuscular control).[12 15] Current evidence indicates that several specific sensorimotor mechanisms (eg, neurocognitive processing capabilities, neuromuscular control and coordination, and regulation of postural control) are not fully developed by the average ages of pubertal onset for girls and boys (ages 8–14).[14 16–19] Although not specifically assessing maturation during adolescence, studies have shown these same underdeveloped mechanisms to be associated with increased injury risk.[17 18 20–22] Consequently, consideration of the function of specific sensorimotor mechanisms relative to adolescent maturation may be a necessary first step to determining whether adolescents experience delays or regressions in sensorimotor function and subsequently enhanced understanding of the interface between adolescent development and injury risk.

To date, no systematic reviews have summarised the literature regarding the development of specific mechanisms of sensorimotor function over the course of adolescence. The purpose of this study was to systematically review the literature relative to the following questions: (1) Which sensorimotor mechanisms are not fully mature by the time children reach adolescence? and (2) Is adolescence a period when children exhibit delays or regressions in sensorimotor mechanisms? In this study, sensorimotor function is defined as the individual and collective abilities of the of physiological systems involved in sensory stimuli reception, transmission and processing of the signal within the central nervous system and conversion of the signal to produce motor output.[23]

METHODS

Search strategy

Systematic searches were performed in February 2010 using PubMed MEDLINE (from 1966), CINAHL (from 1982) and SPORTDiscus (from 1985) databases. Keyword selection was designed to capture all aspects of sensorimotor function. PubMed was searched using MeSH term selections for the keywords 'puberty', 'growth and development', 'sexual maturation' and 'adolescent development' in combination with the AND operator and each keyword phrase listed in figure 1. Similar search strategies were used in CINAHL and SPORTDiscus. Articles identified through the keyword searches were reviewed relative to predetermined inclusion and exclusion criteria. Reviews of retrieved articles' bibliographies supplemented the keyword searches.

Study selection

Inclusion criteria were as follows: studies had to have results that related to at least one of the proposed questions, involve humans, be written in the English language and include subjects in the age range of 8–22 explicitly defined as 'healthy'. This age range was selected based on commonly cited limits for normal variation in the onset and termination of adolescence for both males and females.[10] A significant literature base is already available regarding adolescent development of strength and motor skill performances (eg, vertical jump, speed, throwing distance).[10] Studies that analysed strength or motor performances without observation or manipulation of the sensory aspects of sensorimotor function were excluded from this review for two reasons: (1) the proposed questions were directed towards capturing sensory and motor system interactions and (2) skill performances and strength measures incorporate additional variables such as experience, learning, joint position and environment.

Assessment of methodological quality

The research questions for this study were developmental in nature and therefore dependent on observational designs. As there is no consensus on scales appropriate for observational designs,[24 25] a checklist was created for this review using commonly raised methodological concerns for observational studies (see online appendix table 1).[24–26] Two reviewers evaluated each article based on this checklist. A third reviewer was available to reconcile differences between the two initial reviewers.

RESULTS

The search identified 2304 studies, of which 33 studies met the inclusion criteria (figure 2). All 33 studies provided results associated with Question 1 (summarised in appendix table 2).[12 13 27–55] Six yielded results also pertaining to Question 2 (summarised in appendix table 3).[32 41–44 53] In general, all 33 studies utilised methodological designs considered less than ideal for developmental research questions. No studies were comprehensively longitudinal (ie, longitudinal over the entire age range) or systematically representative of the spectrum of adolescent ages. However, some studies did utilise samples that went beyond simple, cross-sectional designs.[17 32 33 38 42–44 48–50 52 53]

In addition to limitations listed on the assessment checklist, some studies did not adequately consider high intersubject and sex-specific variability. Five studies reported large inter-subject variability within age groupings[32 43 48 49 54] and 10 studies reported significant differences between adolescent males and females for certain sensorimotor mechanisms.[12 17 28 32 33 42 44 49 51 52] Two studies reported no differences between sexes for the observed measures.[13 50] However, both used pooled groups representing wide age ranges, which could have masked differences between the sexes at specific points during adolescent development.

Although many studies were designed to capture similar aspects of sensorimotor function, there was little consistency between studies in how variables were operationalised, measured, manipulated, analysed and interpreted (appendix tables 2 and 3). Conclusive results related to the proposed questions were not possible given the following shortcomings: lack of longitudinal data, poor representation of the adolescent age range, inconsistent use of variables and methods, unaccounted for sex-specific differences and high intersubject variability.

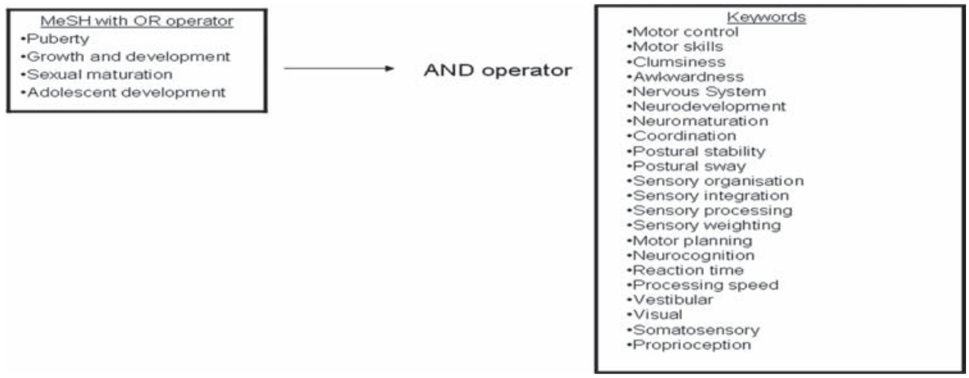

Figure 1 Keywords search strategy.

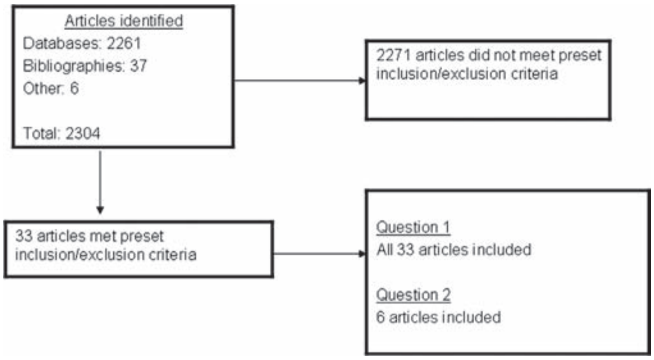

Figure 2 Article search process flowchart.

Nonetheless, a synthesis of the studies' findings highlights several interesting trends.

With regard to Question 1, 12 studies investigated aspects of sensory reception, perception and integration with respect to age,[12 13 27–36] five studies considered age-related changes in signal conduction and processing[19 27 37–39] and 20 studies investigated developmental aspects of neuromuscular/postural control and coordination.[12 16 17 31 35 36 40 42–49 51–55] All 33 studies provided evidence that at least some aspects of sensorimotor function are still developing during adolescence. For Question 2, all six studies indicated that certain sensorimotor abilities may regress during puberty.[17 32 42–44 53] On the whole, these trends support the views that many sensorimotor mechanisms are not fully mature by around the average expected age of pubertal onset (ages 8–14), and at least some children experience regressions in some sensorimotor mechanisms.

Question 1: Which sensorimotor mechanisms are not fully mature by the time children reach adolescence?

Visual mechanisms

Visual mechanisms of sensorimotor control help detect orientation of the body in space and environmental hazards.[15] Several studies indicate that children aged approximately 14–16 may already have well-developed abilities for visual perception of static objects and peripheral vision, whereas dynamic perception and utilisation of visual cues for postural control continue to mature throughout adolescence.[13 27 28] In comparison with adults, children (including young adolescents) appear to be more dependent on visual cues and more easily affected by visual stimuli.[12 29] For example, children exhibit longer adaptation time and greater magnitudes of postural responses in the presence of visual changes.[12 29]

Somatosensory mechanisms

Somatosensory inputs include cutaneous sensations and proprioceptive cues from muscle and joint sensors.[15] Somatosensory cues are critical for postural stability because they provide information about orientation relative to support surfaces.[15 23] Sigmundsson *et al*[32] reported a trend of improved proprioceptive sensitivity with age (sample of ages 5–12). Pickett and Konczak[30] concluded that although adolescents (ages 11–13) are relatively accurate in terms of passive motion sensitivity, their movement detection times are slower than those of adults.

Studies that investigated somatosensory contributions to postural stability yielded inconsistent results. Hirabayashi and Iwasaki[28] found that proprioceptive contributions may stabilise to adult level by ages 3–4, whereas Schmid *et al*[31] and Viel *et al*[12] found that integration of proprioceptive information improves as children get older and may continue to improve even past age 11. The differences between the conclusions may be due to the usage of a composite postural stability score (ie, maximum centre of pressure displacements) by Hirabayashi and Iwasaki. In contrast, Schmid *et al*[31] looked at a variety of sway parameters (ie, mean velocity, mean amplitude, sway area) and Viel *et al*[12] looked at control strategies for body orientation and segmental stabilisation. The additional measures in these latter studies may have increased the likelihood of including a measure sensitive enough to detect subtle differences in postural stability between children and adults.[12 28 31]

Vestibular mechanisms

The vestibular system (ie, semicircular canals and otolith organs of the ear) detects linear and angular acceleration of the head and contributes to postural stability and control.[15] Results from the studies identified for inclusion in this review indicate that vestibular contributions may be the slowest sensory system associated with postural control to mature.[28] In addition, girls' vestibular systems may mature earlier than boys' vestibular systems with significant differences identified between boys and girls aged 7–8 and 9–10, respectively.[28 33]

Multisensory re-weighting mechanisms

Sensory inputs are not always in alignment with one another. For example, sitting in a car may provide proprioceptive information that your body is stagnant, whereas visual cues of objects passing the window and vestibular cues of head acceleration provide conflicting information. Mature neuromuscular and postural control mechanisms rely on a person's ability to adequately up- or down-weight sensory cues appropriately with conflicting sensory inputs.[29] The ability to re-weigh sensory inputs was observed in children as young as 4 years old.[29] However, numerous studies report that children are less capable of adapting, slower to adapt and adapt in a less calibrated way to sensory conflict compared with adults.[19 29 31 33 35] In particular, children struggle with efficient calibration of postural stability when multiple sensory cues are in conflict with one another.[34 36]

Signal conduction and processing mechanisms

Signal conduction and processing mechanisms relate to how fast, efficient and effective sensory cues are received and processed into motor programmes. Evidence indicates that neural conduction speed is similar to that of adults by early childhood: however, neuron excitability and inhibitory properties mature continually from age 9 to 22.[19] Comparisons of functional magnetic resonance images indicate that there is also a developmental shift in where within the brain sensorimotor processing occurs.[38 39] For example, between childhood and adulthood, visuomotor processing appears to switch from a process occurring primarily in subcortical structures to strategies of greater cortical dominance.[27] Improvements in anticipatory responses and ability to repress planned responses may relate to a maturational shift in processing towards increased localisation to regions of the brain thought to play critical roles in motor planning and inhibition.[37 38]

Neuromuscular and postural control

Neuromuscular and postural control are aspects of sensorimotor function that use somatosensory, visual and vestibular signals for reference frames about the location of the body in space.[23] Streepey and Angulo-Kinzler[16] reported that adolescent children (mean age of 10.7) demonstrate postural control similar to adults during simple balance challenges but exhibit similarities to younger children during more challenging postural tasks. Studies show that between childhood and adulthood, there is a shift in postural control from ballistic adjustments greater in amplitude and velocity to smoother, more frequent oscillations.[31 43] Children also show less postural stability in anterior-posterior directions, which may be a sign of an underdeveloped ankle strategy for postural adjustments.[40]

Three of the identified studies explored neuromuscular control for a single joint (knee) during landing from a jump throughout different stages of pubertal maturation.[17 42 44] Using classifications based on a modified Pubertal Maturation Observational Scale (PMOS; which uses maturational indicators of growth spurt, menarcheal status, body hair, sweating and muscular definition),[9] these studies showed that from puberty to postpuberty stages, boys and girls demonstrate a divergence in neuromuscular control. Girls tend to exhibit decreased knee control during and after puberty whereas boys demonstrate no regressions and perhaps even a progression in knee control.[17 42 44]

Intersegmental/interlimb coordination

Coordination refers to the ability to execute smooth, accurate and controlled motor outputs.[15] Good coordination is characterised by appropriate speed, direction, muscular tension, timing and synergistic muscle recruitment.[15] All of the identified studies related to coordination showed progressive improvement in coordinative abilities during the adolescent age span.[45–49 51 52 54 55] However, Largo *et al*[48 49] noted that developmental improvements are often highly variable between children of the same age and influenced by the level of complexity of the task.

Largo *et al*[48] found that improvements in repetitive simultaneous coordinative tasks plateau around ages 12–15 whereas alternating and sequential movement patterns continue to improve up to age 18. Milling-Smith *et al*[51] found that control for in-phase skills (eg, two fingers tapping at same time) matures earlier during adolescence than antiphase skills (two fingers moving in opposite directions). Collectively, these results indicate that coupled movement control is mastered earlier during adolescence than uncoupled, segmented movement patterns.

Inability to suppress coupled movements can also be an indicator of decreased movement control.[15] Associated movements are defined as involuntary, coupled movements with body parts not actively involved in the goal of a given task (eg, moving opposite arm along with the arm performing goal-directed motion).[14 49] Largo *et al* observed that duration and degree of associated movements decreased from age 5 to 18. However, there is a great deal of variability in degree and duration of associated movements for all ages.[49]

Several studies found that as children get older, they demonstrate increased ability to volitionally generate appropriate muscle tension for a task, exhibit more mature synergistic activation of postural control muscles and show improved voluntary control of sway.[45 50 54] Saavedra *et al*[53] reported that by ages 10–15, children also begin to show improved ability to isolate eye, hand and trunk movements from each other. Likewise, Vallis and McFadyen demonstrated that adults tend to anticipate obstacle avoidance with a single, smooth change in trajectory. In contrast, children tend to partition obstacle avoidance into two steps: change of trajectory of head and trunk in an en bloc style (body moving as a single unit instead of independent segmented parts that work together in a coordinated fashion) followed by a change in trajectory.[55] These studies indicate that during adolescence, individuals develop more advanced anticipatory strategies that are less calculated and can be executed more quickly.

Question 2: Is adolescence a period when children exhibit delays or regressions in sensorimotor mechanisms?

There appears to be a paucity of studies directly related to this question. However, six studies provide evidence that regressions may occur in several sensorimotor mechanisms. Sigmundsson *et al*[52] found that proprioceptive sensitivity follows a non-linear developmental trend for both boys and girls with a period of regression around age 8 for girls and around age 9 for boys. Kirshenbaum *et al*[43] and Saavedra *et al*[53] found regressions in motor control characterised by periods of 'over-control' in which children appear to sacrifice speed and variability in movement for the sake of accuracy and control. Three studies report that during the transition from prepubertal to pubertal stages (based on the PMOS), neuromuscular control of knee motion and landing forces is significantly worse in females than in males, with females showing regressions in control abilities.[17 42 44]

DISCUSSION

Sensorimotor function during adolescence

Historically, many studies that investigated adolescent motor awkwardness utilised motor skill performance as a measure of sensorimotor abilities.[9 10] The results from such studies have been inconsistent. For example, Davies and Rose[9] assessed motor skill performance of adolescents grouped by pubertal status and found no evidence of impaired coordination during the pubertal stage, whereas Loko *et al*[56] found that female adolescents (ages 13–14) exhibited plateaus and regressions in multiple motor skills. Others have reported that the effects of maturation may lead to a period of motor regressions for some but not all children, and decline does not necessarily occur in all tasks for the same individual.[10] Results from a set of longitudinal studies on Belgian boys indicated that performance of some boys declined during adolescent growth spurts, whereas that of others only progressed.[10 57]

As described in the Methods section, using motor skills as indicators of motor control abilities is problematic. This systematic review was designed to account for the possibility that specific mechanisms of sensorimotor function may affect and be affected by the various maturational processes that a child experiences during adolescence. From one perspective, a logical hypothesis leading to increased motor awkwardness during adolescence could be that specific sensorimotor mechanisms are not fully mature by the time a child undergoes a rapid growth spurt thus increasing the challenge of even simple motor control tasks. From another perspective, maturational processes may lead to regressions in the function of specific sensorimotor mechanisms as the child's body adjusts to the many rapid changes that occur during puberty. In either case, it is possible that although motor skill performances may not suffer as a child enters adolescence, regressions may occur in specific aspects of motor control such as neuromuscular control, postural stability and intersegmental/interlimb coordination during adolescent growth processes.

Although the inclusion/exclusion criteria set forth for this review were designed to investigate adolescent maturation and specific sensorimotor mechanisms, it was difficult to draw strong conclusions about whether motor control is compromised during adolescence because few studies used designs that could adequately capture non-linear aspects of development (periods of regression within the more generalised progressive trends). A majority of the studies used cross-sectional chronological age–group comparisons (eg, comparisons of younger children with older children or older children with adults). The limitations of such approaches are problematic for three reasons.

First, cross-sectional study designs tend to assess the status of subjects only once. Therefore, regressions that occur within subjects would not be captured. Second, as several studies indicated, high intersubject variability within age brackets may be present. Thus, the use of age-group comparisons based on group means would be extremely limited. In fact, the broader the age range used for a cross-sectional group, the greater the chance regressions could be cancelled out by progressions (especially during a period like adolescence when changes may occur rapidly). Cross-sectional designs also embrace an underlying assumption that progressions or regressions happen in an all-or-none fashion such that all children either experience regressions during puberty or not. In reality, it may be that only some children experience regressions or delays whereas others only experience progressions. Finally, the use of chronological age is a limited view of maturation. A variety of other means of categorisation and quantification of maturational status, such as peak height velocities, percent of adult stature and maturational scales, such as the PMOS, are available, which may help generate a richer characterisation of individual subjects' maturational status than chronological age alone can provide.[9 41] Likewise, the results suggest that future research in this area would greatly benefit from longitudinal study designs that specifically seek to address the limitations of conventional cross-sectional research approaches.

Although the methodological qualities of the included studies were not ideal, in general, the results of these studies indicate that at least some adolescents experience delays or regressions in at least some aspects of sensorimotor function. The methodological limitations of the included studies constrain the understanding of when during the maturational spectrum sensorimotor abilities stabilise into adult levels. The discrepancies in results highlight the importance of using study designs capable of capturing non-linear progressions/regressions as well as measures that are sensitive and specific enough to uncover differences between children and adults.

Likewise, the results emphasise that many sensorimotor system changes that occur during adolescence cannot be fully appreciated through simple, external means of observation of movement. For example, Hausdorff *et al*[47] and Haddad *et al*[46] found that children exhibit less regularity in their gait dynamics and less deterministic centre of pressure trajectories (more random, less structured movement patterns) during complex reaching tasks. Both studies used non-linear analytical tools to capture differences in the temporal order and structure of the variability of movements. It is likely that the differences in movement quality observed in these studies are too subtle to be visible to the human eye or obtainable by conventional linear methods. As Hausdorff *et al*[47] proposed, these understated aspects of movement may provide a good reflection of the ongoing development of the more complex aspects of motor control. Consideration of such aspects of movement complexity gives rise to entirely new avenues for the identification of injury risk factors and understanding of how maturation affects these risk factors. For example, such techniques have successfully helped refine understanding a number of topics including differences between individuals at high risk and low risk for a fall,[58] postural instability in individuals with Parkinson's disease,[59] altered postural control after cerebral concussion in athletes[60] and altered gait variability in individuals with anterior cruciate ligament reconstructions.[61] Therefore, a thorough objective assessment of movement quality in adolescents may warrant more use of non-linear analyses.

One particularly interesting aspect of a synthesis of the results is the concept that adolescents may experience a transient neglect of proprioceptive input exhibited by a regression in their proprioceptive sensitivities.[12] Research on postural stability in younger children shows that during stages when children have to master new postural challenges (eg, standing and walking), they increase their reliance on visual cues.[62 63] Some scholars believe that because pubertal growth can create new postural challenges, adolescents may also regress in their ability to integrate proprioceptive inputs and increase their reliance on visual cues.[12 62 63]

In addition, this proprioceptive regression may have a direct impact on the increased time frame needed for full maturation of postural/neuromuscular control and intersegmental/interlimb coordination. Proprioceptive inputs are a key contributor to regulation of postural control.[15] Therefore, delayed development or regressions in proprioceptive sensitivity could have an impact on adolescent motor control abilities. Consequently, maturation of proprioceptive sensitivity may correspond with development of advanced postural control abilities. Likewise, neuromuscular control of individual joints is inextricably linked to proprioceptive sensitivities from both joint and muscle receptors. The timing of the regression in proprioceptive abilities during adolescence may help explain the regression in neuromuscular control of the knee observed during adolescence in females.

Furthermore, good postural stability may be a prerequisite for enhanced ability to couple and uncouple movements in isolated, coordinated fashions.[43 53 55 62] Like the decrease in ballistic control of posture observed with maturation, some scholars hypothesise that children transition from ballistic control of all systems to more flexible, independent and coordinated control of multiple systems and body segments.[43 53] It has been proposed that the ability to isolate movements improves as children develop the ability to use different body segments as frames of reference around which to stabilise the rest of their body.[62] Early in childhood and during transitional phases of development, children tend to utilise postural strategies that are en bloc in form (eg, head and trunk move as one unit). However, with improved control, children begin to explore new degrees of freedom and challenge their limits of stability that leads to the ability to coordinate movements in more sophisticated, articulated ways.[43 53 62 63]

Further advances in our understanding may evolve from determination of precisely how prevalent such regressions are, how consistent the timing is across subjects and how the variability in the timing of development affects the presence or absence of a stage of motor awkwardness within adolescents. For example, future research may address such questions as: (1) How consistently does a regression in proprioceptive sensitivity occur prior to a rapid growth spurt, during a rapid growth spurt and/or immediately following a rapid growth spurt? (2) How does the timing of such changes influence postural and neuromuscular control? and (3) Do certain patterns of timing of these changes correspond with increased injury risk?

What is already known about this topic?

Although adolescent motor awkwardness and increased injury susceptibility have long been speculated and researched, there is no consensus about the presence of adolescent motor regressions or how such regressions might affect injury risk.

What does this study add?

This systematic review is unique in its consideration of the development of specific sensorimotor mechanisms. Results indicate that many aspects of sensorimotor function continue to mature throughout adolescence and that some children experience regressions in several sensorimotor mechanisms. This systematic review also exposes several weaknesses in our knowledge base.

Adolescent sensorimotor function and injury risk

During adolescence, many children increase activity frequency and intensity levels as they begin to compete in middle and high school athletics. Immature sensorimotor mechanisms and/or regressions in sensorimotor function that coincide with this time frame could, in theory, create a period of high vulnerability for injury. Unfortunately, as limited as our understanding of adolescent sensorimotor function is, the relationship between adolescent sensorimotor function and injury risk is even less well understood.

The results of this review indicate that many variables associated with sensorimotor function are not fully mature by the time children reach adolescence and some specific mechanisms of sensorimotor function may even undergo periods of regression during adolescence. Deficits in a variety of these same sensorimotor mechanisms are correlated with higher injury risk.[18 20–22 64] However, understanding how and when these specific sensorimotor mechanisms independently and jointly affect adolescent injury risk remains unclear.

Numerous studies support deficit-targeted prevention programmes as effective strategies for reducing risk factors and incidence for many sports injuries.[65–68] Insufficient knowledge about sensorimotor function during adolescence may be limiting opportunities to identify additional risk factors and children highest at risk. An enhanced understanding of the longitudinal development of sensorimotor mechanisms and adolescent injury risk is crucial for improving the efficacy of injury prevention programmes.

CONCLUSION

Although adolescent motor awkwardness and increased injury susceptibility have long been speculated and researched, there is no consensus about the presence of motor regressions or how such regressions affect injury risk. This systematic review is unique in its consideration of the development of specific sensorimotor mechanisms. The current findings indicate that many aspects of sensorimotor function continue to mature throughout adolescence, and at least some children experience delays or regressions, in at least some sensorimotor mechanisms. This systematic review also exposes several significant weaknesses in our knowledge base. What is not clear is how specific sensorimotor mechanisms develop throughout adolescence or how these mechanisms contribute to adolescent injury risk. These knowledge gaps are critical barriers because they hinder methods for identifying children at high risk and diminish the efficacy of targeted prevention programmes.

Assessments of the methodological quality of the identified studies highlight several important directions for future research: (1) data should be collected in a longitudinal/repeated measures format, (2) designs should allow for analyses of significant sex differences and intersubject variability and (3) multiple measures of maturational/developmental status should be used in order to provide a more robust picture of the longitudinal course of sensorimotor function during adolescence. Future studies would also greatly benefit from the use of measures known to be sensitive and specific enough to capture subtle differences between subjects and analytical tools that are able to portray the temporal order and structure of movement data (eg, non-linear analyses).

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