

Motor Development during Infancy and Early Childhood: Overview and Suggested Directions for Research

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The development of motor competence during infancy and childhood is dependent upon and influenced by the growth and maturity characteristics of the child interacting with the environment in which a child is reared. Environmental opportunities and restraints for movement interact with the biological substrates of growth and maturation to determine the motor repertoire of the child. This paper provides a brief overview of motor development during infancy and early childhood and then highlights several specific areas and/or questions: critical evaluation of stages for specific movement patterns; extension of the dynamical systems framework; genotypic contributions to motor development; metabolic and physiological correlates of motor development; relationship of motor development to the growth of the brain, status at birth and early postnatal growth; and social contexts of motor development.

Keywords: stages, dynamical systems, brain growth spurt, developmental milestones, somatic growth

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Introduction

Acquisition of competence in motor activities is an important developmental task of childhood. All children, except some with severe disabilities, have the potential to develop and learn a variety of fundamental movement patterns and more specialized motor skills. Such activities are an integral part of children's behavioral repertoires and provide the medium through which children experience many dimensions of their environments.

The development of motor competence during infancy and childhood is dependent upon and influenced by the growth and maturity characteristics of the child (morphological, physiological, and neuromuscular). The environment in which a child is reared is also important. Environmental opportunities and restraints for movement interact with the biological substrates of growth and maturation to determine the motor repertoire of the child.

This paper has two objectives. Motor development during infancy and early childhood is briefly reviewed. Although the refinement of competence in basic and more advanced movement skills continues through

childhood and adolescence into adulthood, this is not considered. Motor development in the context of specific theoretical frameworks and determinants is then considered. Issues or questions for further research are highlighted.

What Is Motor Development?

Motor development is the process through which a child acquires movement patterns and skills. It is a continuous process of modification that involves the interactions of several factors: (1) neuromuscular maturation; (2) the physical growth and behavioral characteristics of the child; (3) the tempo of physical growth, biological maturation and behavioral development; (4) the residual effects of prior movement experiences; and (5) the new movement experiences. All of these occur in the context of the physical and sociocultural environments within which a child is reared. Environmental experiences interact with growth and maturation to influence motor development and proficiency.

Overview of Motor Development

Several features of early motor development are considered: reflexes of infancy, developmental scales, development of upright posture and independent walking, and development of other movement patterns. The overview is not intended as a comprehensive discussion.

Early Motor Behavior

The motor responses of the newborn infant have their roots in fetal behavior. Information on the early development of behavior comes from surgically removed fetuses, direct recording of fetal movements by means of ultrasound during normal pregnancy, and studies of infants born at varying gestational ages see [Saint-Anne Dargassies, (1966); Smotherman and Robinson, (1988)].

Simple extension-like movements of the upper part of the spine can be detected with ultrasound as early as 5 to 6 weeks post-menstrually. Movements of the arms and legs can be detected by about 8 to 9 weeks post-menstrually. Subsequently, there is a rapid increase in different kinds of movements. Neuromuscular changes are age-specific prenatally. The fetus born at 28 weeks of gestation, for example, is neurologically different from a fetus of 26 weeks or of 30 weeks, and the fetus born at 30 weeks of gestation is quite different from the fetus born at 36 weeks [Saint-Anne Dargassies, (1966)]. Primary reflexes, muscle tone, reactivity, motility, and sensorimotor behaviors tend to be specific for each gestational age.

Longitudinal observations for preterm infants born between 28 and 32 weeks of gestation indicate that neuromotor development is a function of gestational age and is also apparently independent of stimuli provided by the extrauterine environment [Brandt, (1986)]. The neuromotor development of preterm infants of appropriate gestational ages is a continuation of the prenatal pattern of functional development.

Advances in ultrasound technology and sensory transducers have permitted accurate monitoring of fetal motor activity in utero and thus complement maternal reports of fetal activity. Fetal movements increase during the first half of pregnancy. On the average, motor activity is reduced from 20 weeks gestation through term, but the vigor of movement increases. Males are, on the average, more active than females. The reduction in activity with advancing gestation is related to space constraints in the uterus associated with fetal growth and probably changes in the fetal nervous system associated with maturation and sleep-wake cycles. Nevertheless, there is

considerable variation in movement activity among individuals during the last trimester of pregnancy [Eaton and Saudino, (1992); DiPietro et al. (1996)].

The motor responses of the fetus reflect in part the immediate needs of the developing fetus, labeled by Oppenheim (1981) as ontogenetic adaptations. Activity is a part of the developmental process. Spontaneous activity is important for normal prenatal development of muscles and joints. Fetal motor activity is also responsive to the uterine environment, which can be quite noisy (e.g., noises associated with the maternal digestive tract and blood flow, maternal voice). Sudden noises in the external environment can also elicit fetal motor responses. In contrast, fetal movements are reduced when mothers are smoking compared to times when they are not smoking. Fetal motor behaviors can also be viewed, to some extent, as precursors of subsequent postnatal movement behaviors and the development of locomotor and manual control in infancy [Smotherman and Robinson, (1988)].

The motor responses of the newborn infant are extensions of those established during fetal life. They take the form of reflexes and reactions that are either present at birth or appear during infancy. Some of the reflexes are quite simple and are mediated at the spinal cord level; others are more complex and require the integration of brain stem centers, the labyrinths, and other developing nervous centers. Reflexes of infancy are often viewed as primitive (those associated with feeding and the eyes, grasp reflex, Moro and startle reflexes) and postural (tonic neck, righting and labyrinthine reflexes). The primitive reflexes are well developed between birth and about 3 months of age, after which there is a decline in their intensity. Postural reflexes begin to emerge at about 3 months of age and increase in intensity of response throughout infancy. As cerebral control develops during infancy, specific reflex activity is gradually inhibited and incorporated into emerging voluntary movements [Capute et al., (1978)]. Although the newborn infant possesses no effective means of locomotion, certain responses resemble later voluntary movements. Included among these locomotor reflexes are reactions similar to creeping, standing and stepping.

The motor activity of the neonate does not involve true volitional activity, and the reflexes indicate a lack of inhibition of the segmental apparatus of the nervous system by higher neural centers. As the central nervous system gradually matures in infancy and childhood, inhibitory functions of the cerebral cortex begin to operate, and reflex movements are gradually inhibited by higher brain centers and are integrated into developing movement patterns as the higher brain centers are differentiated. There is, however,

Table 1 Percentiles for ages (months) at which healthy, full term infants attain developmental milestones leading to independent walking.¹

Developmental Milestone	Boys Percentiles			Girls Percentiles		
	10	50	90	10	50	90
Roll to supine	3.7	5.0	6.2	3.8	5.2	6.7
Roll to prone	4.8	6.0	8.8	4.6	6.0	8.7
Pivot ²	5.0	6.4	8.6	4.7	6.8	8.8
Crawl on stomach ³	6.1	7.0	8.7	5.8	6.9	8.9
Creep on hands/knees	6.8	8.3	10.4	6.5	8.8	11.8
Creep on hands/feet	8.1	9.0	11.8	7.7	9.6	11.9
Sit up	7.3	9.1	11.8	6.8	8.9	11.5
Stand at rail	7.4	8.4	9.8	7.1	8.7	10.5
Pull to stand	7.5	8.5	11.3	7.3	8.9	11.5
Cruise at rail ⁴	8.0	9.5	11.7	8.0	9.8	11.8
Stand momentarily	9.9	12.4	15.6	9.8	12.5	14.9
Walk, one hand held	9.2	11.5	13.0	9.5	11.8	13.5
Walk alone	10.8	13.0	15.9	11.0	13.1	15.7
Walk up and down stairs	16.2	18.9	23.7	16.0	19.7	23.8

1. Adapted from Largo et al. (1985). Data are based on 56 boys and 55 girls from the second Zurich Longitudinal Study.

2. Pivoting - child on stomach moves in circular manner by actions of arms and legs.

3. Crawling on stomach – child pulls forward by coordinated action of arms and legs.

4. Cruise at rail – sideways walking while holding on to a table or similar stable object.

considerable variation in reflex responsiveness among infants as well as within the same infant. Reflexes also vary with behavioral states. The reflexes of infancy are expressions of the immaturity of the developing nervous system and provide a means of assessing the integrity of neuromuscular maturation processes early in life. The absence, delayed appearance or disappearance, persistence, or reappearance of certain reflexes may be indicative of neurological disorders.

Developmental Scales

Development of voluntary control of movement begins in infancy. During the first 2 years of life, the child gradually attains postural, locomotor, and prehensile control. The term developmental milestone is often used to denote the acquisition of control and coordination of specific voluntary movements during infancy and childhood. These early motor achievements are important components in developmental scales [e.g., Bayley Scales of Infant

Development, Bayley, (1969, 1993); see also Bayley, (1935, 1965)]. Such scales are used to evaluate the integrity of the developing central nervous system in infants and young children, but one of their main applications is as a screening device to identify children with developmental problems, or who might be at risk for developing such problems [e.g., Denver Developmental Screening Test, Frankenburg and Dodds, (1967); Frankenburg et al., (1992)]. Emphasis is on early identification and diagnosis so that physical therapy or other forms of intervention can be initiated as necessary.

Age-associated variation for the attainment of specific motor milestones during infancy and early childhood indicate levels of overall motor development that infants and young children are expected to demonstrate by particular ages. Data for a sample of Swiss infants followed longitudinally are summarized in **Table 1**. The range of interindividual variation in early motor development is substantial. The sequence of development is reasonably uniform,

but shows variations and occasional omissions (see below). Such occurrences are aspects of normal variability - the individuality of motor development and perhaps of variation in rearing environments, but in some instances may be indicative of developmental problems or delay. Sequence variation in early and subsequent motor development needs further study.

Development of Independent Walking

Independent walking is the major motor development task during the first 2 years of life. It is also perhaps one of the most important human behaviors. Upright locomotion in the form of bipedal walking is evident in the hominid fossil record some 3 to 4 million years ago and has been a major force in the evolution of the human species.

The developmental changes leading to walking behavior are essentially a series of postural changes through which the child gains the motor control necessary to first assume upright posture, then to maintain upright posture, and finally to walk independently. The general sequence of developmental changes leading to walking behavior can be summarized as follows. The infant gradually attains control of the head, upper trunk, and upper extremities. Control of the entire trunk follows, first in the development of sitting posture with support and then sitting alone. This is followed by active efforts at locomotion by means of prone progression, i.e., crawling on the stomach or creeping on the hands and knees. Active efforts at upright posture follow, the child standing first with support and then without support. The same applies to early efforts at walking, first with support as along a table or with the assistance of an adult. Finally, independent walking develops. Initial efforts at walking are usually characterized as "stiff-legged", "jerky" and "flat-footed", with a wide base of support and the arms outstretched for balance.

Changes in locomotion leading to independent standing and walking are evident in the data summarized in **Table 1**. The range of normal variation in ages at attaining each stage should be noted. Sex differences are small and inconsistent. Changes from rolling over to standing and walking are reasonably uniform in neurologically unimpaired full term and preterm infants. In this sample, 87% of the boys and girls progressed in the following sequence: rolling over, pivoting, crawling on the stomach, crawling on hands and knees, crawling on hands and feet, standing and walking. On the other hand, 13% of the sample showed a different sequence of progression: 6% of the infants progressed from crawling on the hands and knees to standing and walking, 2% progressed from

crawling on the stomach to standing and walking, and 2% progressed from pivoting to sitting up to shuffling and to standing and walking. The remainder showed variable sequences, for example, bridging instead of crawling on the stomach [Largo et al., (1985)]. The movement experiences of infants can influence variability in crawling behavior. For example, infants who crawled on their stomach showed more proficiency in crawling on the hands and knees than those who did not crawl on their stomachs [Adolph et al., (1998)]. Unfortunately, this study did not relate crawling behavior to independent standing and walking.

Age at walking is perhaps the most common landmark of early motor development. Error in maternal recall and problems of definition need attention. Walking is variously defined as first steps, first steps alone, taking a step unassisted, walking a few steps without support, taking at least three steps without support, minimum of 10 steps alone, and walking well. Allowing for these caveats, evidence for a sex difference in age at walking is not consistent. Moreover, the range of variation in reported means and medians among studies in the United States and Europe is relatively narrow, about 2 to 3 months. This is especially noteworthy because the range is based on data that span about 50 years [see Malina, (1980)].

Once walking is initiated, proficiency develops at an exponential rate. Stride length, speed of walking, and cadence increase; and movements show greater reproducibility as the walking pattern becomes more like that of an adult. Stride or step length is related to the physical size of the child, and specifically to length of the lower extremities. There is a parallel increase in leg length and step length as skill in walking develops during early childhood. Rotation of the hips increases gradually and contributes to the increase in stride length. Stride also includes specific actions of the foot and knee. In the mature walking pattern, foot and knee actions include knee extension prior to or coincident with the heel striking the surface, knee flexion during the middle portion of the support phase, and knee extension when the heel is lifted off the ground as the next stride begins [see Gomez Pellico et al., (1995); Hausdorff et al., (1999)].

Balance is very important in the refinement of walking and the development of other motor skills. Initial walking efforts are characterized by a wide base of support, with the feet relatively far apart and the toes pointed outward. As walking proficiency develops, the base of support gradually narrows, so that the feet are placed within the lateral dimensions of the trunk and the toes point more forward. Arm movements gradually become synchronous with the stride of the legs, so that there is opposition of

movement.

This is the general developmental sequence for walking. Independent walking does not indicate the achievement of the mature walking pattern. The mature pattern develops gradually after the onset of independent walking. By about 5 years of age an adult walking pattern is established in the majority of children. However, stride dynamics are variable among children and vary with walking speed.

Walking affords the child a new and more rapid means of locomotion, with many possible variations. It also frees the hands from their role as supports, so that a variety of manipulative experiences and skills are possible. Hence, the walking pattern can be viewed as the foundation upon which other movement patterns and skills develop.

Fundamental Movement Patterns and Skills

As walking is refined, control of movements improves so that a considerable amount of independent locomotion and increasing experimentation with a variety of movements are possible. The experimentation occurs in a variety of contexts including the home, play areas in the community, and preschool among others and contributes to the acquisition of competence in fundamental movement patterns. These basic patterns are the foundation upon which other movements and combinations of movements are developed and refined.

A good deal of early and current motor development research describes the temporal, spatial, and sequential elements of specific movement patterns as they develop during childhood. The specific elements are summarized in a sequence of stages from an immature to a mature pattern for a specific fundamental movement [see Robertson, (1982, 1984)]. The definition and delineation of stages are to some extent arbitrary. Stages are superimposed on an ongoing process of development, which is not necessarily continuous. Progress in motor development appears to be continuous when data are grouped and reported in terms of average trends. There is, however, considerable variability among children. Some may show relatively long periods of stability or minimal change followed by a burst of progress; others may regress to less mature stages before progressing to a more advanced stage; and still others may show seemingly continuous progress. A key factor in monitoring change in stages of development is the interval between observations. There is a need for observations over relatively short intervals, perhaps 2-3 months for some patterns.

Although stages are somewhat arbitrary and have limitations, they are a convenience to facilitate

the observation and understanding of the motor development of young children. The sequence for the overhand throw was perhaps the first to be described in a developmental context and thus has historical relevance in the study of motor development [Wild, (1938)]. Others have described the sequence of development of the overhand throw in a bit more detail, but the sequence of changes are basically the same [Robertson, (1978)]. More detailed quantitative analysis of the kinematic properties of the overhand throw, e.g., angular velocity of elbow extension or angular velocity of shoulder adduction, or angular velocities of specific joints at ball release [Yan et al., (2000)], are generally consistent with the developmental model described by Wild (1938).

Developmental sequences for a variety of fundamental movements are described in introductory textbooks on motor development [Wickstrom, (1983); Haywood and Getchell, (2001); Payne and Isaacs, (1999)]. The descriptions include locomotor (running, jumping, hopping, galloping, skipping), projection (throwing, kicking, striking), and reception (catching) skills.

The stages in the sequential development of fundamental movement patterns and skills are, as noted above, somewhat arbitrary and need to be validated. They are convenient for observing and documenting the motor development of children. Some stages consider the body as a whole (whole body sequences) whereas others consider rather specific components of the movement pattern (body component sequences). This distinction is important for a child might be at an immature or intermediate stage in one component of a movement and at a more advanced stage in another component at a given age. This would suggest dysharmonic motor development for this basic pattern. This potential source of variation in motor development has not been systematically studied for the basic motor skills. There is, on the other hand, potential for microanalysis of a pattern, which may have limited value. Focusing on elbow action in the overhand throw, for example, runs the risk of overlooking the overall pattern which includes actions of the legs, trunk, shoulder, and hand-wrist. Components do not exist in isolation of the total movement pattern and it is important to keep this in focus.

Studies of the specific temporal, spatial, and sequential elements of basic motor skills are usually based on detailed analysis of film and video records of individual children performing specified tasks, such as a vertical jump or hopping on one foot. The studies are both cross-sectional and longitudinal, but presently available longitudinal data on the development of a variety of movement patterns have

Table 2 Estimated ages (months) at which 60% of children performed at specific developmental stage for several fundamental motor patterns: B=boys, G=girls.¹

Fundamental Pattern	Stages									
	1		2		3		4		5	
	B	G	B	G	B	G	B	G	B	G
Run	23	20	27	25	40	40	51	62	-	-
Standing long jump	23	24	47	48	76	76	117	120	-	-
Overhand throw	10	10	40	44	45	56	50	73	63	102
Hop	34	28	46	41	64	58	90	86	-	-
Skip	59	56	65	63	78	70	-	-	-	-
Catch	24	23	41	40	51	50	73	61	80	77
Strike	24	23	32	34	44	46	88	101	-	-
Kick	22	20	40	47	56	73	90	99	-	-

1. Adapted from Seefeldt and Haubenstricker (1982). Number of stages from immature (Stage 1) to mature varies for each basic skill. The last stage indicated is the mature stage; other stages indicate intermediate stages. The data were provided by courtesy of Dr. Vern Seefeldt, Michigan State University.

not been systematically analyzed in a longitudinal manner. There is relatively little emphasis on intra- and interindividual variability within and between stages, and relatively little quantitative analysis.

Developmental sequences for nine fundamental movement patterns have been described as a part of the Motor Performance Study at Michigan State University [Haubenstricker et al., (1999)]. This mixed-longitudinal study provides insights into the development of fundamental motor patterns. Ages at which 60% of children met the criteria for specific developmental stages for each of the nine fundamental motor patterns are shown in **Table 2**. Several trends are suggested. Development progresses rapidly and continues well into middle childhood for some movement patterns. Boys tend to attain each stage of overhand throwing and kicking earlier than girls, whereas girls tend to attain each stage of hopping and skipping earlier than boys. The difference between boys and girls is most marked for overhand throwing. The sex differences may be related to cultural influences on practice and appropriateness of activities that involve these movement patterns. The attainment of specific stages, especially stages 2 and 3, of the other fundamental skills (running, jumping, catching and striking) shows considerable similarity between boys and girls. However, there is more variation between boys and girls in the ages at which the final or mature stages are attained. For example, girls attain

the final two stages of catching earlier than boys, although they do not differ in ages at attaining the earlier stages. In contrast, the difference between boys and girls for attaining the mature form of the standing long jump is small.

The data also suggest variation in the interval between ages at the attainment of specific stages for a given fundamental motor skill. For example, the intervals between the four stages of jumping are quite large, whereas the interval between stages 3 and 4 for striking appears to be quite large compared to those between the earlier stages (**Table 2**). Variation in the time between stages is, in part, a function of the relative arbitrariness of the definition of each stage for a specific skill. For example, the defined changes from one stage to the next may be too great, or the stage demands may be too difficult. An additional factor is individual variation in the time required to master each stage of a specific motor skill and the interval between observations in a longitudinal series.

The stages of motor development during childhood should be addressed in the context of several questions which need attention in motor development research, assuming the stages are correctly described and are valid. (1) What is the expected duration of a stage within each fundamental movement pattern? What is the extent of variability in the duration of a stage? (2) What is the relationship between the age at entry into a specific stage and subsequent progress through

Table 3 Percentage of children at each age rated as proficient (easy coordinated performance) in several fundamental motor skills.¹

Motor Skill	n	Age Range	Age in Months			
		in years	36-47	48-59	60-71	72-83
Climbing	358	2 - 7	50	75	72	92
Jumping	140	2 - 7	42	58	81	84
Hopping	160	4 - 7		33	76	84
Skipping	227	2 - 7	0	14	72	91
Galloping	139	4 - 7		43	78	92
Throwing	113	2 - 7	0	20	80	74
Catching	167	3 - 7	0	29	56	63

1. Adapted from Gutteridge (1939).

the stage? If a child enters stage 2 of the standing long jump later than average, does he/she progress through the stage more quickly than a child who enters stage 2 earlier than average? (3) What are the characteristics of children who progress through stages of a specific pattern quickly compared to those who do so more slowly? Do they differ in size, physique, body composition, prior movement experiences, opportunities for activity, and so on? (4) What is the relationship, if any, between ages at attaining specific stages of a movement pattern, or duration of progress through the stages, and subsequent motor performance? (5) Within a single chronological age group, say 4 year old children, what are the characteristics, behavioral and physical, of children who show immature compared to those who show mature movement patterns for a specific task? (6) What is the relationship among stages for several fundamental movement patterns? (7) Are ages at entry into the mature stage for the fundamental movement patterns related? If so, might this suggest a general "motor maturity"? These and other questions have not traditionally been addressed in motor development research.

Movement patterns for most fundamental patterns ordinarily develop by 6 or 7 years, although the

mature patterns of some skills do not develop until later. As the movement patterns are refined through practice, quality of performance improves, and the patterns are integrated into more complex movement sequences, such as those required for specific games and sports. However, some 6, 7 and 8 year olds have not developed sufficient motor control to successfully accomplish the fundamental motor skills. Although **Table 2** shows the ages at which 60% of children attain specific developmental levels for fundamental movement patterns, note that 40% of the children have not attained the specific developmental levels by these ages. Similar trends are indicated in an early observational study, i.e., subjective evaluations, of movements summarized in **Table 3**. The percentage of children rated as proficient increases with age between 2 and 7 years, but a significant number of 6 and 7 year old children are not yet proficient in the fundamental movements.

Some research has assigned scores to stages, progressing from the immature to the mature pattern [Sinclair, (1971)]. Observations in a mixed-longitudinal sample of children 2-6 years of age indicate that scores generally improve, on average, with age on most tasks, but not necessarily in a smooth progression. Mature movement patterns

(as defined) are attained in most skills by about 4 or 5 years. Catching and hitting, manipulative patterns that require eye-limb coordination, are exceptions; scores do not indicate mature patterns over the age range studied. Kicking approaches the mature pattern, on the average, at 5 or 6 years.

Young children may show a relatively mature pattern of movement at one age and an immature pattern at a subsequent age. This is suggestive of the concept of "reciprocal interweaving" (Gesell, 1954), which suggests that alternating from mature stages to less mature stages, and then back to mature stages is common in development. Such seemingly irregular developmental trends often occur without any recognizable cause and may reflect normal variability. The trends may be related to the fact that young children are developing and learning many new skills, so that when a mature pattern is attained in one task, the child might attempt other movement pursuits that detract from the mature pattern originally demonstrated. The result may be a reversal to a less mature movement pattern. For example, a child may have mastered the overhand throw from a stationary position, but may revert to an underhand pattern when trying to throw while running. Or, a child may have mastered catching a large ball, but may revert to a less mature pattern when trying to catch a smaller ball.

Variation in motor development within individual children, between children, and from age to age within the same child is considerable during early childhood. The stability or instability of motor development across age during early childhood has not received attention in contrast to the motor abilities of older children and adolescents [see Malina, (1996)]. Children often show a tendency to perform well on one occasion only to perform poorly on the next. Variation in performance between testing periods probably reflects normal variation in growth (changes in body size and proportions), neuromuscular maturation, opportunity for practice, motivation to perform in the test situation, and perhaps the adults administering the tests and cooperation of young children. The adult factor in research with children is not considered in motor development research, but probably should be considered as a potential source of variation in the motor achievements of children. An additional factor that must be recognized in explaining variation among children is error in observing and rating movement patterns.

The preceding approaches to the development of fundamental motor skills focus on the stages leading from immature to mature patterns in the form of discrete, though somewhat arbitrary, stages. Another approach is more quantitative and focuses on the products or outcomes of specific performances of

young children that are done under standardized conditions. The motor tasks, performed under specified conditions, are amenable to accurate measurement, although the performances of young children may not be reliable within and between days. Performance tests are introduced as early as 3 years of age. Note, however, many children may not have sufficiently mature movement patterns to perform the task as described in the test protocols.

Allowing for these caveats, performances of children 3-6 years on standardized tests of motor proficiency tend to improve, on average, more or less linearly with age [Ferenc (1981); Morris et al., (1982); Parizkova et al., (1984)]. Examples include the distance a ball is thrown, the distance the body is projected in a standing long jump or in a vertical jump (jump and reach), the time elapsed in completing a 30 yard dash, balancing on one foot for as long as possible, and others. Sex differences are generally small and there is much overlap between boys and girls. On average, boys perform better in tests of running, jumping and throwing, and girls perform better in balance during early childhood. Some tasks, e.g., catching, show negligible differences between boys and girls. The differences between boys and girls probably reflect types of activities available for preschool children, availability of suitable role models for motor performance, and societal expectations for these young ages.

The assessment of motor skills during early childhood is also important in the context of screening, prediction and intervention. Similar to scales of infant development described earlier, these scales are designed to screen for developmental problems or risk for such problems. The Peabody Developmental Motor Scales, for example, were developed to assess "... the relative developmental skill level of a child, identify skills that were not completely developed or not in the child's repertoire, and then plan an instructional program to develop those skills" [Folio and Fewell, (1983, p. 1)]. The scale assesses fine and gross motor development in children birth to 7 years of age, and includes many of the motor milestones and fundamental motor skills described above. A comprehensive discussion of a variety of scales for the assessment of motor development in infancy and early childhood is provided by Burton and Miller (1998).

Dynamical Systems

The framework that currently dominates the field of motor development is dynamical systems [Thelen and Smith, (1994); Lewis, (2000)], which emphasizes the ongoing interactions among the child (growth and behavioral characteristics), the environment (specific

environmental circumstances) and the motor task (development of specific movements). Dynamical systems are complex and interconnected, have many different components, and are characterized by self-organization. Dynamical systems, as the name implies, continuously change; they operate in different time scales and levels such that there is variation in temporal-spatial patterns. Behavior emerges from self-organization and it is difficult to describe emerging behaviors in advance.

Motor development of the infant and young child is viewed as emerging from the interactions among (1) the child (performer – size, proportions, body composition, biological maturity, cognitive abilities, etc.), (2) environment (rearing atmosphere, opportunities, stimulation, object size in manipulative tasks, etc.), and (3) movement task (hip-knee-ankle action in walking, upper-lower extremity coordination in crawling, etc.). The child, environment and task are labeled constraints. Changes in the constraints and their interactions function to guide or channel the motor system or motor development [Newell, (1986)]. Note, however, that children are dynamic beings, who, as they increase in age, become capable of making decisions on how they interact with the environment even when presented with specific environmental opportunities or stimulation.

Motor development is thus the outcome of the interaction of the growing and maturing child, specific motor tasks and the environment. The terms body scaling and action scaling are often used in the context of dynamical systems. Child-environment interactions, for example, should be viewed in the context of changing body dimensions and proportions (body scaling) and improving levels of motor competence (action scaling). Body size, proportions and composition change as the child grows, and levels of motor proficiency change as the child develops. These in turn influence the nature of the interactions between the child and his/her environments. The child's perceptions of the environment in the context of his/her physical and motor characteristics are related but important factors affecting motor development.

Specific applications of dynamical systems concepts to the development of movement patterns of young children are somewhat limited. In an interesting example, six 3 and two 7 month old infants were "trained" daily to step on a slowly moving treadmill. "Training" is a manipulation of one of the constraints, i.e., the environment, in an effort to channel an emerging motor behavior. The "training" resulted in improved stepping. Those infants whose stepping behavior was unstable at the start seemed to benefit more from the practice on the

treadmill. The results of this experiment suggest that the developing motor system can be influenced by "training" and that infants have their own preferred stepping patterns which interacted with the "training" on the treadmill [Vereijken and Thelen, (1997)]. The authors interpreted the results as indicating that the neuromuscular pathway for stepping is in place in infancy, and that stepping emerges in the context of practice on the treadmill. There is a need, for example, to relate such "training" to independent walking and subsequent development of other movement patterns by young children. Thelen and Ulrich (1991) provide a more detailed discussion of treadmill stepping in the context of treadmill speed and coordination between the legs during the first year of life. The dynamical systems approach to the transition from independent walking to running has been applied to four children observed at about 6, 8 and 10 months after the onset of independent walking and then at 3 years of age [Whitall and Getschell, (1995); see also Whitall and Clarke, (1994)]. Changes in control parameters or constraints (stride characteristics - length, time, velocity, center of mass, intralimb coupling, and knee and ankle actions) were described. With the exception of intralimb coupling, all parameters showed continuous change. Though interesting, the results are limited to small samples, largely descriptive, and basically qualitative. The results suggest the need for quantitative modeling of the data and inclusion of other potential control parameters associated with the child and the environment.

Genetics of Motor Development

The sequential age-related appearance of motor milestones during infancy and early childhood was historically considered to be the product of a genotypically controlled neuromuscular maturation [McGraw, (1945); Gesell, (1954)]. In contrast, current views stemming from dynamical systems emphasize the ongoing interactions among development of specific movements, growth characteristics of the child and environmental circumstances. Nevertheless, the contribution of the genotype cannot be overlooked.

Information on the contribution of inherited characteristics to motor development is rather limited (see Bouchard et al., 1997, for a more comprehensive review). In general, early motor development assessed with the Bayley Scales of Infant Development is more concordant in monozygotic (MZ) twins than in dizygotic (DZ) twins [Wilson and Harpring, (1972); Saudino and Eaton, (1991)]. The results also suggest a role for shared environmental influences, e.g., mutual imitation and pressures for similarity.

Difficulties in testing infants and young children, e.g., stranger anxiety and crying, are factors that need to be considered among sources of potential variation.

Data for specific movements (crawling, running and walking) also suggest greater concordance in MZ twins, but much of the data is derived from descriptive comparisons of single pairs of twins [Bouchard et al., (1997)]. Corresponding information on the motor development of biological siblings (who share one-half of their genes in common) are limited. Data from one study indicate variable heritabilities (0 to 0.42) for several developmental milestones – ages at turning, sitting up, standing alone and walking, in siblings [Livshits, (1988)].

Although considerable effort has been devoted to documenting developmental stages for a variety of fundamental movements, little is known about the contribution of inherited characteristics to the development of movement patterns in twins and siblings. Two studies of older twins, 6-9 years [Goya et al., (1991, 1993)] and 11-15 years [Sklad, (1972)], suggest a significant contribution of inherited characteristics to variation in the kinematic structure of running a dash, i.e., greater concordance for MZ compared to DZ twins. Among the older youth, differences in the kinematic features of the dash were smaller between female MZ and DZ twins compared to male MZ and DZ twins [Sklad, (1972)]. This may suggest that the running performance of girls is more amenable to environmental influences, including social and motivational factors for an all-out performance in a dash. In contrast to the dash, intrapair differences in the kinematic features of a throw and swimming crawl were similar in MZ and DZ twins 6-9 years of age [Goya et al., (1991, 1993)]. It is likely that environmental influences related to instruction, practice and experiences have an important role these two motor skills.

There is a need for further study of the estimated contribution of genotype to motor development in healthy infants and children. Genetic influences on motor development may also be inferred from studies of individuals with genetic anomalies, many of whom show delayed development of postural control and independent walking and also poorer scores on gross and fine motor scales in childhood [Bouchard et al., (1997)].

Metabolic and Physiological Correlates of Motor Development

Information about the physiological and metabolic substrates of motor development is lacking. How does early motor development relate, for example to skeletal muscle composition and metabolic

characteristics? Data for infants with delayed development provide some insights.

Children who do not walk independently by 17-18 months of age are often classified as late walkers and referred for clinical evaluation. Dissociated motor development - a condition characterized by delay in the gross motor domain, no abnormal neurological signs, and normal fine motor development - is associated with late walking [Lundberg, (1979); see also Haidvogel, (1979)]. Among 65 children who could not walk at 17 months, 79% had a late pattern of learning to sit or dissociated sitting development. They sat unsupported without using the arms at the normally expected age, but were very delayed in attempting to sit actively without help. In addition, 51% of the late walkers had a locomotion progression that involved shuffling (in a sitting position with or without use of the arms and hands) in contrast to crawling, and 71% had muscular hypotonia, especially of the lower trunk and lower extremities. These observations suggest a triad of factors that may be related to late walking – dissociated development of sitting, a shuffling locomotor progression, and muscular hypotonia [Lundberg, (1979)].

The late walking in 35 of the 65 children (54%) was idiopathic, i.e., without a known cause. It is perhaps of interest that 13 of the 35 children with idiopathic late walking presented a family history of shuffling, which may suggest a possible genetic influence [Lundberg, (1979)]. In a subsequent study, samples of muscle tissue of 6 idiopathic late walkers were analyzed. This small sample of idiopathic late walkers showed reduced muscle fiber size, especially Type II fibers, and lower concentrations of ATP, phosphocreatinine and glycogen compared to normal children of the same age who walk at the normally expected time [Lundberg, (1980); Lundberg et al., (1979a)]. These characteristics may be related to physical inactivity. Similar trends occur with muscular atrophy, while training can increase fiber size and concentrations of metabolic substrates. Nevertheless, reduced concentrations of stored metabolic substrates of muscle tissue, or impaired substrate mobilization, may have implications for motor development. For example, children with celiac disease also have reduced muscle concentrations of ATP, phosphocreatinine and glycogen, and are also delayed in motor development compared to healthy children of the same age. Celiac disease is characterized by diarrhea, and if it persists, it is associated with growth stunting and thin extremities, which may suggest muscle wasting. With treatment, i.e., a gluten-free diet, levels of muscle substrates and motor development of these children are similar to normal control subjects [Lundberg et al., (1979b)].

In contrast to reduced size of Type II muscle fibers in children with idiopathic late walking, three boys with a syndrome of extreme delay in motor development, among other clinical features, had a predominance of Type II fibers in the vastus lateralis muscle [Qazi et al., (1994)]. The Type II fibers were also considerably larger than Type I fibers. Some of features of the syndrome are similar to a disorder described as congenital fiber type disproportion [Harper, (1989)].

Data for low birth weight infants also provide some insights on physiologic correlates of motor development. With progress in neonatal care, very low birth weight (<1500 grams) and extremely low birth weight (<1,000 grams) infants survive into adulthood. Very low birth weight associated with prematurity is related to depressed motor development, which is probably influenced by the delayed physical and neurological immaturity of these infants. Low birth weight associated with prenatal growth restriction, i.e., small-for-date infants, is also associated with delayed motor development during infancy.

Extremely low birth weight has implications for motor development and performance at older ages. Children with birth weights <1,500 grams or <1,000 grams show performance deficits on scales of fine and gross motor development and on tests of muscular performance [Marlow et al., (1989); Pohlman and Isaacs, (1990); Powls et al., (1995); Small et al., (1998); Falk et al., (1997); Keller et al., (1998)]. Anaerobic muscle performance is also limited in children of extremely low birth weight, even among those who show no overt manifestations of a neuromuscular disability [Falk et al., (1997); Keller et al., (2000)]. Deficient anaerobic power is associated with reduced muscular strength [Ericson et al., (1998)], but may also result from reduced motor coordination and slower reaction time [Keller et al., (2000)], and uncoordinated generation of forces during a vertical jump [Falk et al., (1997)].

The results highlight the need to extend studies of motor development to its metabolic and physiological bases. A related question is the potential influence of systematic instruction and practice. Would such a program assist children of extremely low birth weight to catch-up to age- and sex peers of normal birth weight?

Early Motor Development and Growth of the Brain

Brain growth is very rapid during infancy and early childhood, continuing the growth pattern of the brain and associated tissues that began prenatally. Dobbing and Sands (1973; see also Dobbing, 1990)

have described the rapid growth of the brain prenatally and postnatally as a “brain growth spurt.” The spurt is a period of rapid growth that begins at about mid-pregnancy and continues through about 4 years of age. The early part of the spurt, from mid-pregnancy to about 18 months of age, is characterized by rapid multiplication of glial cells; the later part, which lasts until about 4 years of age, is characterized by myelination. Glial cells are basically support cells for the primary nerve cells, the neurons, which develop quite early in pregnancy. Myelin is a fatty sheath, which covers the axons of nerve cells. During myelination, the myelin sheath gradually thickens around the existing axon and is deposited in sheaths around new parts of the axon as it grows in length. Myelin is related to the transmission of nerve impulses - the greater the thickness, the more rapid the impulse transmission.

The proposed brain growth spurt does not include the early part of pregnancy, i.e., the differentiation and development of neurons and neuronal migration, and probably the early stages of differentiation and development of glial cells. These influence the overall cellular population of the brain, the formation of neuronal circuits and basic cellular architecture of the brain [Morgane et al., (1993)], and thus also have implications for functional development, including motor development in infancy and childhood.

Motor development in infancy and early childhood is related to the rapid growth of the brain and central nervous system at this time. This reflects to a large extent neuromuscular maturation. Environmental conditions are also important and interact with these biological processes to influence the expression of motor development so that it is almost impossible to partition biological from environmental effects in early motor development.

The association between early motor development and growth of the brain is especially apparent in infancy and may be related to the unique growth spurt of the cerebellum. Functions of the cerebellum include the development and maintenance of neuromuscular coordination, balance, and muscle tone. In contrast to the growth spurt in numbers of glial cells in other regions of the brain, the cerebellum starts its spurt later than the forebrain (cerebrum) and brain stem but completes its spurt earlier. The forebrain and brain stem begin their spurts at about mid-pregnancy; the cerebellum begins its spurt a month or so before term. However, by 18 months of age the estimated cell content of the cerebellum has reached adult levels, while the estimated cell contents of the forebrain and brain stem have attained only approximately 60% of adult numbers. Thus, the cerebellum apparently experiences the first part of the growth spurt over

a shorter period of time and at a faster rate than other areas of the brain. It is also during this time that the infant develops the postural control and balance necessary for independent walking, so that a potentially important role for the cerebellar growth spurt can be inferred.

In addition to changes in cell number and myelination, remodeling of the cerebral cortex and changes in electrical activity (electroencephalographic activity) also occur. Analyses of the thickness, neuronal density, and histology of the cerebral cortex of "normal" children at autopsy (usually accidental deaths) indicate that each hemisphere and lobe of the brain, and each area and layer within each lobe has its own rate of development [Rabinowicz, (1986)]. There appear to be at least three or more periods of brain maturation postnatally. The first occurs between 15 and 24 months of age, during which almost all areas of the brain reach a similar level of maturity. The second occurs between about 6 and 8 years of age and involves remodeling of the cerebral cortex (changes in thickness and neuronal density), and results in altered dendritic patterns and increased neuronal density. Although it is not yet clearly established, there may be two periods of change in the maturation of the cerebral cortex during adolescence. The electroencephalographic data also suggest several periods of heightened activity or spurts (Thatcher et al., 1987), but their definition, location in the brain and timing differ somewhat from the anatomical data. More recent data based on magnetic resonance imaging of the brain also suggest structural maturation of neural pathways which support motor functions during late childhood and adolescence [Paus et al., (1999)]. Results of these studies have potential implications for understanding motor development and performance. However, the links between such observations and motor development remain to be established.

Status at Birth and Subsequent Motor Development

Early motor development is also related to a number of factors that operate before and at the time of birth. For example, fetal movements during the last 3 months of pregnancy have been related to motor development during the 1st year, whereas the motor status of newborn infants has been related to motor development scores later in infancy. The viability of the infant at birth and shortly afterward is ordinarily based on ratings of heart rate, breathing, muscle tone, reflex responsiveness, and color (Apgar scores). Earlier studies have related Apgar ratings taken at one and five minutes after birth to motor development

at later ages [Rosenblith, (1966); Edwards, (1968); Black et al., (1979)]. Newborns that experienced respiratory instability, for example, are characterized by delayed motor development later in infancy.

The significance of such associations between status at or shortly after birth as well as the specific operation of such influences in mediating or modifying motor development is not clear. An infant's status at birth, especially birth weight, is strongly related to maternal characteristics. Among full term infants with birth weights in the normal range, weight at birth is not consistently related to early motor development [Solomons and Solomons, (1964)], to the age of walking alone [Pineau, (1961)], or to gross motor coordination at about 4 years of age [Edwards, (1968)]. There also does not appear to be an association between mode of delivery and ages at sitting and walking, and fine and gross motor coordination at three years of age [Silva et al., (1979)].

Early Postnatal Growth and Motor Development

Information on the relationship of motor development to the growth status of infants and young children is not extensive. Some early observational data suggest that muscular and small-boned infants and those with a linear frame walk at an earlier age [Shirley, (1931)]. Infants with a larger estimated fat-free mass attain higher scores on gross motor tests during infancy, and leg muscle mass (as measured on radiographs) at six months of age is predictive of walking unaided at one year of age [Garn, (1966)]. Corresponding data for a longitudinal sample of French infants suggest that later walking in boys is associated with reduced estimated fat-free mass, whereas later walking in girls is associated with a higher level of estimated relative fatness [Patois et al., (1974)].

The first two years of life are characterized by a rapid rate of linear growth and also by rapid changes in motor development. Daily measurements during the first two years indicate that growth in length proceeds in an episodic (saltatory) manner, i.e., in a series of stepwise increases separated by variable periods of no increase (stasis). Periods of stasis vary from 7 to 63 days [Lampl et al., (1992)]. It would be of interest to relate changes in motor development to episodic growth during the first two years. Is progress in motor development associated with periods of stasis? What is the impact of a growth saltation on motor development?

Evidence from longitudinal studies also indicates a "mid-growth spurt," a slight acceleration in velocity of growth in height (and other dimensions) between

6 and 8 years of age [Malina et al., (2004)]. As in the case of saltatory growth, it would be interesting to relate changes in motor proficiency in to the timing of the mid-growth spurt.

Systematic analyses of the relationships between motor development and specific measures of size, body proportions, and body composition during early childhood are needed. Relationships among 29 anthropometric variables, including somatotype, and balance performance were considered in 3 and 4 year old children [Erbaugh, (1984)]. Seven variables – leg length/tibial height ratio, foot length and breadth, estimated leg muscle area, abdominal and chest circumferences, and ectomorphy – accounted for 55% of the variance in walking on an elevated balance beam (71 cm above the floor). In contrast, five variables – height-for-age, biacromial breadth, abdominal circumference, estimated arm fat area, and ectomorphy – accounted for only 28% of the variance in performance on a stabilometer. The results suggest that anthropometric characteristics contribute differentially to performance on the two dynamic balance tasks. Height and weight as reflected in ectomorphy contribute significantly to performance on both balance tasks.

The results emphasize the need to consider the motor development of children in the context of their growth status. Related factors that need consideration are growth rate and changes in body proportions and composition. Infancy and early childhood are characterized by a relatively rapid rate of linear growth and by changing relationships between height and weight, and between the lower extremities and the trunk. For example, after an increase during the first year of life, the BMI declines to a low value at about 5 to 6 years of age and then increases. Given the association between the BMI and later overweight/obesity, the rise in the BMI after it reaches its lowest point has been labeled the "adiposity rebound" [Rolland-Cachera et al., (1984)]. A question that merits attention is the relationship between individual differences in the age at "adiposity rebound" and subsequent motor development and performance. At the same time as the BMI declines, the ratio of sitting height to standing height declines, indicating proportionally longer legs. As a result, the position of the center of gravity is gradually lowered during early childhood. The position of the center of gravity is important in the maintenance of balance, which is important to motor development. Early childhood is also characterized by a relatively rapid reduction in skinfold thicknesses (subcutaneous adipose tissue) between about 6 months and 3 years of age [Malina et al., (2004)]. Thus, major changes are occurring in body size, proportions and composition during this

time of rapid motor development and experimentation with a variety of motor activities by children.

Social Contexts and Motor Development

Motor development occurs in a social context, e.g., home, play, school, and so on. Each context places specific demands on the motor competencies and physical activities of infants and children. The specific influences of different social conditions have not been systematically evaluated in the context of motor development. Quality of living conditions, family size or number of siblings, interactions among siblings, area of residence (urban-rural, inner city-suburban), and overall socioeconomic circumstances, all of which are related, are potentially important factors to consider.

Variation in rearing atmosphere is frequently indicated as a significant factor influencing motor development during infancy and childhood. Rearing style is a multifactorial construct that has changed through time and has a major cultural component.

An issue of interest is the predictive and explanatory power of rearing differences on motor development. This has not been systematically investigated. Part of the problem is methodological; the nature of parent-child relationships and their situational context are not stable. As such, the translation of observed differences in rearing practices to motor development and performance is difficult. It is well known that cultural conditioning for specific sex-associated roles begins early in life, and that there are sex differences in how boys and girls are reared. Sex differences in motor development during the first year or two of life are not systematically apparent, but by about 3 years of age, sex differences are apparent in some motor tasks and they persist into the school ages. Although there is considerable overlap between boys and girls in early childhood, the fact that sex differences appear at relatively young ages would seem to beg an explanation. Sex differences in early motor competence need to be examined in the context of opportunity for and frequency of practice, appropriateness of models (e.g., how often do girls throw with their fathers?), guided instruction, and so on. These are specific components of rearing style that may more directly relate to the development of competence in motor skills. Potential interactions between growth, maturity and motor characteristics of the child with rearing conditions also need consideration. For example, how do the motor characteristics of a child, or level of motor proficiency, influence the rearing environment? Mothers of infants who were rated as competent on the Bayley scales of development interacted more with their infants

in a manner that focused on the child's abilities and interests [Moore, (1977)]. The characteristics of the child, including motor characteristics, are thus important factors in eliciting specific behaviors from the parents, which may serve to reinforce infant behaviors. These observations need to be extended.

Data relating rearing to motor proficiency at older ages are scanty and at times unclear. One study suggested a positive relationship between a high disciplinarian attitude of the mother and the development of the standing long jump, but a positive relationship between a low disciplinarian attitude of the mother and the development of overhand throwing [Schnabl-Dickey, (1977)]. Among children in kindergarten through grade 3, social variables that influenced throwing performance varied with age, but generally reflected parental influences, parent-child interactions and play experiences in both sexes [East and Hensley, (1985)]. Interestingly, the influence of social variables on throwing performance decreased with age, suggesting that the influence of social factors decreased with increased proficiency. Results of such studies, of course, are only associational. Specific motor patterns might differ in degree of environmental sensitivity, which may in turn be related to differential rates of neuromuscular maturation of motor patterns. More specific research is essential to understanding the translation of rearing styles into variation in motor competence.

The influence of rearing on motor development may be mediated in part by the presence of siblings in the household. Thus, a child's position in the family and sibling sex status may be potentially important influencing factors. Does the motor development of an only child differ from that of a child with siblings? Does the sex of siblings have an influence on motor development? Do sibling interactions differ by age and sex?

First born infants generally show advanced motor behavior compared to later born. This observation is generally related to greater maternal indulgence and therefore stimulation of the first born compared to later born children [Malina, (1980, 1983)]. It is not known, however, if the accelerated motor development persists beyond infancy or when a second child is born.

Some evidence indicates age- and perhaps sex-associated variation in movement and observational behaviors of 3 to 5 year old siblings during participation in gross motor activities [Erbaugh and Clifton, (1984)]. Under experimental conditions involving body-oriented and object-oriented motor activities, older siblings initiated performance of body-oriented activities such as climbing and jumping, and repeated and practiced object-oriented tasks such as striking and throwing more than younger

siblings. In contrast, younger siblings imitated the movements of older siblings under conditions of both body-and object-oriented play conditions more often than older siblings imitated the activities of younger siblings. The observations suggest an important role for modeling interactions among siblings, i.e., an older sibling more often serves as a model for the younger sibling. Further, younger boys in this experimental study generally imitated older siblings more often than did younger girls, and younger boys in mixed-sex sibling pairs imitated their older sisters more often than boys in other sibling pairs. It is possible that younger boys simply imitate gross motor activities more than girls, or that older sisters are more nurturing of younger brothers than are older brothers or older sisters of younger sisters.

Summary

This overview is a blend of the old and new in motor development research, and suggests several directions for further research. The majority of motor development research has been primarily descriptive. Description, of course, is essential and provides valuable information.

Motor development of infants and young children is often treated independently of the child's characteristics and the environments. Motor development is a plastic process. Variation in the sequence, timing, and tempo of development and in level of proficiency is related to a variety of biological (genotype, body size and composition, metabolic) and environmental (specific practice, rearing atmosphere, play opportunities and objects) factors which interact in a dynamic manner. Children too are dynamic beings and in many ways choose how they wish to interact with a specific environment even when presented with specific environmental opportunities or stimulation. The specific contributions of such factors and their interactions to variation in motor development during infancy and early childhood need to be established in more complex research designs.

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Main Works:

- C. Bouchard, R.M. Malina and L. Perusse (1997) *Genetics of Fitness and Physical Performance*. Champaign, IL: Human Kinetics
- N. Maffulli, K.M. Chan, R. Macdonald, R.M. Malina, and A.W. Parker, editors, 2001. *Sports Medicine for Specific Ages and Abilities*. London: Churchill Livingstone
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- R.M. Malina, C. Bouchard, O. Bar-Or (2004) *Growth, Maturation, and Physical Activity*, second edition. Champaign, IL: Human Kinetics (The first edition [1991] was translated into Japanese and Portuguese).

Membership in Learned Societies:

- Phi Epsilon Kappa
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- American Association of Physical Anthropologists
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- Society for Research in Child Development
- American Association for the Advancement of Science
- Human Biology Association
- American College of Sports Medicine
- American Academy of Kinesiology and Physical Education
- International Association of Human Biologists
- European Anthropological Association
- Association of Mexican Biological Anthropologists