The Temporal Structure of the Forward Roll: Inter- and Intra-Limb Coordination

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Williams, K. (1987). The temporal structure of the forward roll: Inter- and Intra-limb coordination. Human Movement Science, 6, 373-387.

Abstract:
Investigations of the temporal structure of actions like walking, running, and hopping have given us information about movement's underlying structure. 'Rules' governing the timing of these cyclic, repetitive skills might be similar to those found for other actions. The forward roll was selected for study because there had been some previous investigation of the course of its development (Williams 1980). Children, aged 5, 7, and 9 years participated in this study. Analysis of the absolute and relative timing of selected actions revealed no statistical differences. A subset of these data was digitized to permit a deeper analysis of the rolling action. Correlation coefficients examining inter- and intra-limb timing relationships suggested the presence of tight coupling between segments in young children. Linkages were found between hip and leg segments as well as between hand contact and leg action. Magnitudes of correlations fell across the ages tested. This pattern of differences suggested that young children constrained their body segments more tightly than older subjects, to offset control problems like balance. Older subjects were more willing, or able to remain off balance for longer periods, in order to build greater speed during performance.

Article:
Until recently, a primary goal of motor development researchers was to chronicle age changes in motor behaviors. Much of the early research consisted of describing skill sequences children might be expected to perform, and their predicted age of attainment (e.g., Gutteridge 1939; McCaskill and Wellman 1938). Sequential changes observed in movement are still of interest to investigators (Clark and Phillips 1985; Roberton 1987; Roberton and Halverson 1984). Rather than being the primary focus of study, however, current research focuses on what these overt changes can tell us about a movement's `deep structure' (Schmidt 1985), or underlying organization.

One aspect of movement under increasing scrutiny is its temporal structure. Investigators have examined questions such as: What are the timing relationships between body segments? Do these relationships change or remain invariant across ages and performance conditions? How does the temporal structure of an action relate to its overt configuration (or is there a direct link)? There is evidence suggesting that tight linkages exist among segments within a limb, as well as there being somewhat looser links between limbs (Whitall et al. 1985; Roberton 1987). In addition, some temporal linkages have been found to remain invariant across ages (Clark et al. 1984), while others emerge over time and then stabilize (Roberton 1987; Roberton and Halverson 1986). These invariances have been identified despite movement topographies that differ greatly across ages and skill levels.

The temporal structure of movement is hypothesized to represent part of the underlying organization of action. Schmidt (1985) took the presence of the nonchanging relative timing of an action as support for motor program theory. He suggested that relative timing parameters were a resident element of motor programs. When a movement is performed under new or different environmental conditions, its underlying timing is specified by the program. Adjustments for specific situations are made by changing other, `flexible' parameters within the program, like absolute timing.

Alternatively, Kelso and Tuller (1984) have hypothesized that a movement's timing is not itself inherent, but emerges as a result of the self-organizing properties of a dynamic system. Muscles are grouped into temporary collectives, constrained to act as units for the purpose of movement production. These temporary groupings are called coordinative structures (Turvey et al. 1982). Timing invariances are hypothesized to occur as a *result*, or byproduct of the action of a coordinative structure (or group of coordinative structures).

Other timing patterns also might emerge from a system's dynamics. Temporary, functional linkages between joint segments might be observed. Although not strictly invariant, high correlations between joint displacements, velocities, or other events, would suggest a temporary cooperation by elements with the system. Such a temporary 'marshaling of forces' would reduce the degrees of freedom within the body, making control more streamlined (Bernstein 1967; Kay et al. 1987). Rather than having to individually coordinate and control actions of arms and legs, body segments could be constrained as larger units for the purpose of performing a specific movement. Because linkages emerge as a result of specific demands placed on the mover (from the movement context, as well as from gravitational and nonmuscular forces), muscular coalitions would be dynamic, shifting as necessary from one action to another.

Most investigations of movement timing invariances have involved adults (Shapiro et al. 1981; Viviani and Terzuolo 1980). Subjects practice an action under one set of conditions and then attempt it under a different set (e.g., other speeds or amplitudes). Although subjects increase the size of words as they write (Vivian and Terzuolo 1980), movement durations remain nearly constant. Shapiro et al. (1981) found that most parts of a step cycle retained the same relative timing, despite dramatic changes in absolute walking and running speeds.

Motor development researchers are exploring whether similar coordinative relationships may be found in developmentally young subjects (Clark et al. 1983; 1984; Roberton 1987). Clark et al. (1983; 1984) found that young walkers demonstrated 'adult-like' coordination between the legs approximately 3 months after the onset of walking. With support, newly walking infants also exhibited adult-like interlimb patterns (Whitall et al. 1985). Roberton (1987; Roberton and Halverson 1986) investigated temporal changes in hopping. Intra-limb invariance in the time from landing on the support leg to its point of deepest knee flexion was revealed. She also discovered the *emergence* of some timing patterns. For example, partially validated developmental sequences for hopping included a change in the swing leg from little or no movement to a 'pumping' action (Halverson and Williams 1985). Although some children moved the swing leg as early as 4 years, its timing, relative to knee extension of the support leg, was quite variable until around 9 years of age. After that, this interlimb pattern of coordination also became invariant across the remaining 9 years of her study.

Most of the work examining the temporal structure of movement has involved either repetitive, cyclic tasks like running and walking, or simple arm movements. Other types of motor skills also might exhibit similar timing patterns. Previous study of the course of development of the forward roll (Williams 1980) resulted in its selection for further investigation. In addition, the forward roll is a discrete action, making it different from previously studied, cyclic skills. Therefore, the purpose of this investigation was to expand knowledge of timing patterns within a specific movement by (a) examining the forward roll globally for evidence of timing invariances; and (b) investigating coordination within and between the limbs as a means of examining its deeper structure.

Methods

Subjects

Forty-nine children, aged 5, 7, and 9 years participated in this study: 5-year-olds: $n = 16$; $M = 66.6$ months, $SD = 2.5$; 7-year-olds: $n = 16$; $M = 89.5$ months, $SD = 2.8$; 9-year-olds: $n = 17$; $M = 114.2$ months, $SD = 3.2$. Each group contained an approximately equal number of males and females. All children were volunteers selected from a single elementary school in Madison, Wisconsin. Parents signed informed consent forms, approving their child's participation.

Each subject was filmed from the side using a motor-driven high speed (64 fps) DBM Milliken camera. Subject-to-camera distance was 9.14 m. Individual subjects performed their rolling trials on a 1.22 m by 2.44 m mat, placed perpendicular to the optical axis of the camera lens. They began in a standing position at the edge of the mat. Following a ready signal, subjects performed a single roll at their own pace. They were asked to try to return to a standing position, if possible. Each subject performed at least 5 trials.

Data analyses

Absolute and relative timing invariants

Two-hundred seven trials were available for analysis: 66 from the 5-year-olds' sample; 67 from the 7-year-olds'; 74 from the 9-year-olds' trials. Frames for the onset/ending of key actions were identified by examining individual trials using a Dynamic Frame motion analyzer (Model DF-168). Events were selected only from the 'force producing' portion of the action: hand contact, head contact, beginning of knee extension, hips vertical, toes off. Since gravitational influences were minimal prior to toe off, force production was considered complete when a subject's feet left the ground. Relative timing data were computed from the first movement forward from the standing position (defined as the beginning of knee flexion), to toes off.

Rater objectivity for identifying the occurrence of each event was determined. Rater agreement was within a single frame (±15 msec), for most events. Head contact was difficult to observe consistently, however, so a less stringent criterion was applied: intra- and inter-rater agreement within 2 frames (± 30 msec) was accepted as adequate.

Absolute times for the onset/cessation of an action were computed, based on the known frame time (15.6 msec). Relative times were determined by comparing the absolute time of an event with the roll's total time (i.e., first forward motion to toes off). This calculation resulted in a percentage of the total time for that particular action. Actions of interest were hand contact, head contact, hips vertical, and initiation of knee extension. Actual overall duration also was examined. Multivariate analyses of variance (MANOVAs) were performed on absolute and relative dependent variables to examine the global question of whether timing invariances occurred in the forward roll.

Kinematic analyses

To perform more fine-grained analyses, 35 trials were digitized from the children's data: 5-year-olds' n = 11; 7-year olds' n = 11; 9-year-olds' n = 13. The following criteria were applied, to select one trial from each child's data: (a) the subject began in a fully standing position (he/she was not squatting or had not begun forward movement prior to the camera's being 'up to speed'); (b) both feet left the surface simultaneously, or if not, the left foot (closest to the camera) was the last foot to leave the floor; and (c) joint markers were visible throughout the entire sequence. Data for 14 of the children were unusable, because all of the criteria (particularly criterion (b)) could not be satisfied.

Individual trials were rear projected onto a Graf/Pen sonic digitizer. X- and y-coordinates for foot, ankle, knee, hip, shoulder, elbow and wrist were obtained and smoothed using a low pass digital filter. Because the analyzed part of the movement was not particularly fast, a cutoff of 6 Hz was selected. Displacements of the ankle, knee, hip, and shoulder angles were computed from these smoothed data. Velocities and accelerations also were generated by differentiating angular displacements. Two additional variables were derived from these data: timing of maximum velocities of ankle, knee, hip, and shoulder joints and initiation of extension (frame in which joint reversal occurred) for ankle, knee, hip, and shoulder.

Analyzing the variables generated from this subset of the data made it possible to ask additional questions about the nature of the coordination observed to occur within the forward roll. First, was there a co-ordering of certain events, like the moment of hand or head contact and a joint's reversal? Second, what was the specific relationship between the ankle, knee, hip, and shoulder during the force production phase of the forward roll (does extension occur simultaneously within all four joints, or do they extend sequentially)?

Pearson product—moment correlations were computed to explore relationships between certain discrete events, like joint reversals and hand contact. Additionally, position data were correlated for each joint pair (e.g., ankle vs. knee or shoulder vs. hip).

In order to investigate intralimb coordination within the body, several additional relationships had to be specified. To examine the overlap between two-, or three-, and four-joint configurations, a phase of positive contribution (Hudson 1986) was defined for each joint. A joint's positive contribution was the time from the initiation of joint extension (IE) to maximum velocity (Vm) for that joint. Two-joint pairs first were compared for amount of overlap. This shared positive contribution was the time that two adjacent segments contributed positively divided by the time that either segment made a positive contribution (Hudson 1986: 244). Greater simultaneity, or overlap between segments would be demonstrated by outcomes approaching 100%, while sequential extension would result in low percentages.

The proportion of overlap between three or four segments was examined in a similar fashion by comparing that period when all joints contributed positively, with the overall period of positive contribution. Additionally, the overall period was subdivided into phases of pre-, post-, and simultaneous positive contribution (Hudson 1986). Dividing the total action into these three parts made it possible to examine whether extension in the three- or four-joint configurations occurred sequentially or simultaneously.

Table 1
Average Pearson product–moment correlations for joint pair position data.

Joint pair	Age 5	7	9
Ankle–knee	0.61 [a] (0.33 to −0.97)	0.57 [a] (0.13 to 0.97)	0.35 [a] (−0.18 to 0.94)
Ankle–hip	0.46 [a] (−0.13 to 0.93)	0.47 [a] (−0.12 to 0.94)	0.17 [a] (−0.83 to 0.73)
Knee–hip	0.84 [a] (0.04 to 0.98)	0.91 [a] (0.82 to 0.98)	0.87 [a] (0.62 to 0.97)
Shoulder–ankle	−0.71 [a] (−0.95 to −0.37)	−0.42 [a] (−0.96 to −0.87)	−0.25 [a] (−0.99 to 0.96)
Shoulder–knee	−0.75 [a] (−0.98 to 0.08)	−0.91 (−0.96 to −0.87)	−0.64 [a] (−0.99 to 0.96)
Shoulder–hip	−0.93 [a] (−0.98 to −0.81)	−0.94 [a] (−0.98 to −0.86)	−0.74 [a] (−0.99 to 0.73)

Note: Data in parentheses are the range in correlations for individual subjects.
[a] $p < 0.05$ for $\chi^2 = 13.22$.

Results

Absolute and relative timing invariants

No significant differences were detected when the absolute timing of variables was examined: Hotelling-Lawley Trace: $F_{10,72} = 1.45$, $p = 0.18$. This same result was found for age differences in the relative timing of forward roll parameters: Hotelling-Lawley Trace: $F_{8,74} = 1.09$, $p = 0.38$. Since no age differences were found in either multivariate analysis, absolute timing of selected events was used in the remaining analyses.

Absolute temporal structure: Kinematic analyses

Comparisons were made between angular displacements for each two-joint pair, for each subject (table 1). These correlations were transformed to Z-scores, and tested for within-age differences. All but one Chi-square comparison was significant (shoulder—knee correlation for the 7-year-olds), demonstrating wide variation in the magnitude of correlations within age. The data suggested, however, that 5- and 7-year-olds generally were characterized by tighter joint couplings than the 9-year-olds. On the average, there was a high (negative) relationship between shoulder and hip positions for 5- (— 0.93) and 7-year-olds (— 0.94). Shoulder—hip correlations dropped slightly to an average of — 0.74 in the 9-year-olds. There also was a moderate relationship between the angular positions of ankle and knee for the 5- and 7-year-olds (0.61 and 0.57, respectively). By 9 years, this average correlation dropped to 0.35. A similar pattern was observed in comparisons of ankle—hip and ankle—shoulder actions (table 1). The only relationship that remained high for all three age groups was between knee and hip ($r > 0.84$ for all three groups).

Hand contact, an event which occurs early in the forward roll, might logically have an impact upon other events occurring throughout the rolling action. Intercorrelations were computed between hand contact and (a) initiation of joint extension, and (b) the timing of maximum velocity, for each joint and age group (table 2). The magnitude of these correlations suggested a tight linkage between hand contact and the initiation of extension in all four joints (ankle, knee, hip, and shoulder) in the 5-year-olds (*rs* > 0.81). Correlations between hand contact and the timing of maximum velocities also were very high for the youngest children. This linkage was somewhat weaker for the 7-year-olds, however, especially for the relationship between hand contact and timing of maximum angular velocities (*rs* ranged from 0.64-0.73). Correlations between hand contact and the timing of joint extensions ranged from 0.71 to 0.81 for the 7-year-olds. By 9 years of age, there was virtually no relationship between hand contact and the timing of any of the other variables (*r* s ranged from — 0.12 to 0.40).

Table 2
Pearson product–moment correlations for the timing of hand contact with initiation of joint extensions and maximum velocities.

Variable	Age		
	5	7	9
Ankle extension	0.82 [a]	0.71	−0.12
Knee extension	0.89 [a]	0.81 [a]	0.34
Hip extension	0.90 [a]	0.76 [a]	0.40
Shoulder extension	0.85 [a]	0.74 [a]	0.34
Ankle maximum velocity	0.85 [a]	0.64	0.04
Knee maximum velocity	0.89 [a]	0.69	0.18
Hip maximum velocity	0.87 [a]	0.66	0.04
Shoulder maximum velocity	0.87 [a]	0.73 [a]	0.36

Note: For the 5-year-olds, $n = 11$; for the 7-year-olds, $n = 11$; for the 9-year-olds, $n = 13$.
[a] $p < 0.05$.

Shared positive contribution

The amount of overlap that occurred during the extension phase was examined for each age group. These comparisons were made by computing the percentage of shared positive contribution (SPC) for two-, or three-, and four-joint combinations (Hudson 1986). Excluding the shoulder, adjacent joint combinations exhibited the largest amount of shared positive contribution. Overlap between ankle—knee and knee—hip pairs exceeded 50% in all three age groups: ankle—knee combination: SPC = 58.5% for 5-year-olds; SPC = 58.7% for 7-year-olds; SPC = 51.5% for 9-year-olds; knee—hip combination: SPC = 57.2% for 5year-olds; SPC = 59.0% for 7-year-olds; SPC = 53.5% for 9-year-olds. The amount of overlap was less, and declined across ages for the ankle—hip pair: SPC = 47.9 for 5-year-olds; SPC = 39.5 for 7-year-olds; SPC = 33.2% for 9-year-olds.

There was little overlap between the shoulder and other joints, among the ages tested. For the shoulder—ankle combination, SPC = 33.7% for the 5-year-olds, 35.8% for the 7-year-olds, and 35.6% for the 9-year-olds. For shoulder—knee, SPC was 26.2% for the 5-year-olds, 27.3% for the 7-year-olds, and 35.3 for the 9-year-olds. Finally, shoulder—hip SPC was 28.4% for the 5-year-olds, 32.9% for the 7-yearolds, and 27.2% for the 9-yer-olds.

Three- and four-joint temporal overlap was examined by dividing the overall period of positive contribution into three parts: pre-simultaneous, simultaneous, and post-simultaneous phases (Hudson 1986). All joints contributed positively during the simultaneous segment. There was a wide range in the amount of overlap occurring at each age (0-63%). However, two general patterns were discernible: (1) There was more overlap between three joints than four; and (2) more younger subjects demonstrated greater overlap (longer simultaneous phase).

For three-joint overlap, six of the eleven 5-year-olds had a simultaneous phase that was longer than, or equal to, either of the two other periods. The same number (six of 11) of the 7-year-olds were characterized by relatively longer periods of simultaneous extension in all three joints. Only four of thirteen 9-year-olds had simultaneous phases equal to, or longer than, their pre- or post-simultaneous phases.

Nearly one-half of the subjects at each age (five 5-year-olds, four 7-year-olds, and four 9-year-olds) demonstrated *no* simultaneous extension in all four joints. Excluding these subjects from the analysis still resulted in very short periods of simultaneous extension: 5-year-olds = 25%; 7-year-olds = 24.3%; 9-year-olds = 15.5%. Note, however, that the amount of overlap declines across age, as with the three-joint comparison.

Discussion

The results of this investigation demonstrated several things: First, a failure to find statistical significance for either absolute or relative timing parameters makes it premature to draw definitive conclusions about timing invariances in the forward roll. Second, linkages were found between lower body segments as 5- and 7-year-olds performed the forward roll. These linkages generally were `weakest' in the oldest children studied. Greater overlap between segmental actions for 5- and 7-year olds, compared to 9-year-olds also was found. This finding suggested that younger children performed the forward roll in a slightly more simultaneous fashion when compared to 9-year-olds, who performed it more sequentially (Hudson 1986). Third, high correlations between hand contact and the initiation of joint extension suggested the presence of tight, functional linkages between upper and lower body segments, particularly in younger children. Similar, high correlations between shoulder and hip actions further substantiated the presence of tight linkages in young children.

Absolute and relative timing invariances

In most investigations of relative timing, comparisons are made of movements performed at a variety of speeds. Despite the speeding-up or slowing-down of the overall movement, the relative timing of certain events remains the same. No statistical differences were found for *either* relative or absolute timing parameters in this study, so it is unclear whether relative timing invariances occur in the forward roll. Examining absolute times required for selected events suggests that there may be changes occurring across ages in the forward roll, however (fig. 1). For example, older subjects tended to place the hands on the surface sooner (5-year-olds' M = 569.1 msec; 7-year-olds' M = 554.5 msec; 9-year-olds' M = 480.0 msec), and to complete the roll more quickly (5-year-olds' M = 838.5 msec; 7-year-olds' M = 805.8 msec; 9-year-olds' M = 691.7 msec). Standard deviations of 100-200 msec made it impossible to detect these differences, however. On the other hand, differences in relative times did not approach significance. So, while there may be timing invariances in the forward roll, further investigation, with larger numbers of subjects, performing more trials, will be necessary to discover them.

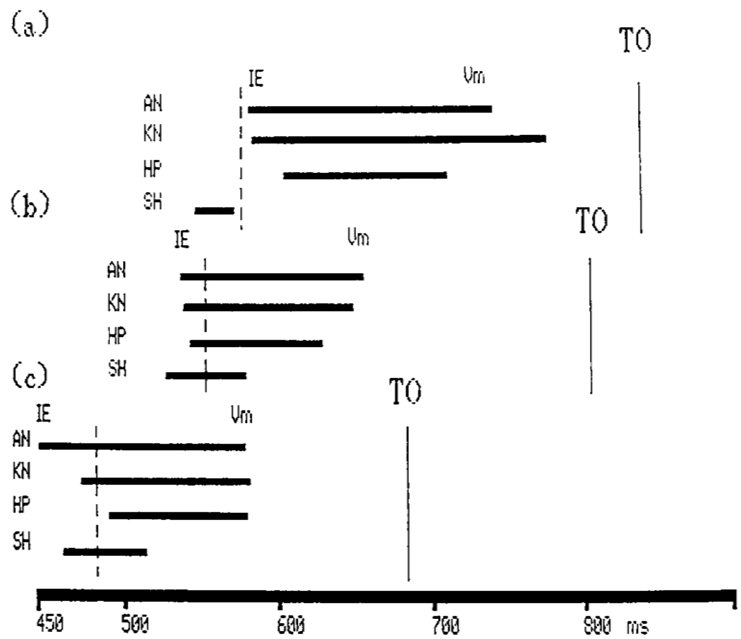

Fig. 1. Absolute temporal relationships between hand contact (vertical dashed line), toe off (TO), initiation of joint extension (IE), and timing of maximum velocity (Vm) for ankle (AN), knee (KN), hip (HP), and shoulder (SH) joints. Only those relationships which occur between the time of hand contact and toe off are shown, based upon the average absolute times for each variable, for 5-year-olds (a), 7-year-olds (b), and 9-year-olds (c).

Intra-limb coordination

Correlations between positions of the lower limb (i.e., ankle and knee) were low to moderate (0.17 to 0.61), even in the youngest children. Only the relationship between knee and hip was high. In all likelihood, those correlations were due to the action of biarticulate muscles spanning both hip and knee joints (i.e., hamstrings). Within each age group, there was a great deal of variability in the magnitude of correlations between joint positions.

Considerable overlap among two- and three-joint combinations occurred in the forward roll. The amount of simultaneous joint extension, particularly in the 5- and 7-year-olds, underscores the minimal speed demands of the task. Skills which require the production of high movement velocities (i.e., overarm throwing) would be characterized by sequential joint extensions — with nearly zero overlap (Hudson 1986). Actions requiring accuracy would be performed using simultaneous extensions. The forward roll fell somewhere in the middle of this continuum. This result was not surprising since the children were asked to perform a roll which would enable them to return to a standing position. The outcome may have been different if subjects were asked to do a dive or aerial roll, requiring more speed.

Older subjects demonstrated less overlap between segments. This was not a strong tendency, however, suggesting that subjects may have had different options in the way they might perform. As suggested above, speed could have a strong bearing on the amount of overlap that was observed. Older subjects may have chosen to generate more speed, resulting in actions nearer a sequential extension pattern.

Inter-segmental coordination

The magnitude of some correlations suggested that young children tightly constrain body segments in order to improve their control. Older subjects, however, were characterized by less constrained linkages. For example, relationships between hand contact and ankle or hip extension were high in young children, but decreased in older performers (table 2). Fig. 1 illustrates the relationship between these events for each of the ages studied. Average times of occurrence clearly depict differences among the age groups. For the 5-year-olds, hand contact occurred prior to any of the other events. Then, initiation of joint extensions (IE) occurred sequentially from the shoulder through ankle, knee, and hip (IE for ankle and knee were nearly simultaneous, however). Maximum velocity (Vm) was attained in the shoulder first, followed by hip, ankle and knee, 150-200 msec after hand contact.

Shoulder extension also led the action for the 7-year-olds. In the other three joints, initiation of extension occurred almost simultaneously. In addition, hand contact did not take place until *after* joint extension began. Maximum angular velocities were reached sequentially from shoulder to ankle joints. In the 9-year-olds, shoulder and ankle extension began well before hand contact, compared to the 7-year-olds. Knee extension began just before hand contact; hip extension started just after hand contact. Shoulder maximum velocity was reached 30 msec after hand contact, while Vm occurred simultaneously for ankle, knee, and hip, approximately 100 msec after hand contact.

Age changes in the ability to balance could explain differences in the order and timing of these events. To minimize time out-of-balance resulting from joint extension (and the consequent movement of their center of gravity outside the base of support), 5-year-olds placed their hands on the surface even before joint extension began. Older subjects took greater 'risks' by reaching forward outside their base of support. Seven-year-olds initiated extension only briefly before putting their hands down, suggesting that they were less willing (or able) to remain off balance than the 9-year-olds.

Placing the hands on the surface prior to joint extension afforded youngsters greater stability during the often unfamiliar inverted position. It would also restrict their movement options, however. Early hand contact would make it more difficult to build speed. Consequently, maximum joint velocities would occur relatively later in the action (fig. 1). By tying joint extension to hand contact, the 5-year-olds functionally linked upper and lower body segments, thereby increasing their stability. They used these linkages to 'put on the brakes'. In contrast, older performers (especially the 9-year-olds) did not form total body linkages. Instead, they seemed to use the off-balance position created by joint extension, to help them to build speed more quickly. Nine-year-olds reached maximum joint velocities relatively sooner than the younger children (fig. 1).

Even very young children, just beginning to complete an identifiable forward roll, were able to coordinate and control their performances. Changes across age occurred in the manner in which children controlled their bodies. For example, interactions between joints, like ankle and knee, are modified, based upon the development of other capabilities, like balance.

The results of this investigation clearly demonstrate the need for further study of timing relationships in the forward roll. In particular, larger numbers of children should be tested, to verify the trends suggested by these data (see Williams (1986) for one such attempt). Longitudinal investigation also is necessary to verify the patterns found in these cross-sectional data. Additionally, children who cannot yet roll without assistance should be tested to determine if similar timing relationships hold prior to successful completion of the skill.

In summary, while evidence for relative timing invariances was equivocal, other timing patterns were discovered. Relationships between temporal events, like hand contact and knee extension, were less strongly linked with increased age. These latter relationships may differ across ages, based upon the ability to produce and control speed. Young or inexperienced performers may be restricted by their ability to balance themselves, particularly where task demands require them to assume an unfamiliar, inverted position. Older, more experienced performers are freer to 'experiment' with options, like the amount of speed produced.

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