Form and Variability During Sit-to-Stand Transitions: Children Versus Adults

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ABSTRACT. In performing the sit-to-stand transition, young children (6- to 7-year-olds) were expected to display a movement form similar to that of adults. However, movement consistency was predicted to be poorer in children than in adults because they lack refinement of motor control processes. Kinematic analysis of 10 repetitions of the sit-to-stand movement was carried out for 6 typically developing children and 6 adults. Supporting the authors' prediction of comparable form, no differences were evident between age groups for sequence of joint onsets, proportional duration of segmental motion, or in angle-angle plots of displacement at 2 segments. In contrast, within-participant variability was found to be higher for children: Coefficients of variation for most kinematic measures were twice those seen for adults. The authors interpret the children's lack of movement consistency as a reflection of inadequate stabilization of an internal model of intersegmental dynamics. Whereas adults have attained a skill level associated with refinement of that model, children have not. Children have an additional control problem because changes in body morphology throughout childhood require ongoing updating of the internal model that controls intrinsic dynamics.

Key words: motor control, motor development, motor learning, intrinsic dynamics, skill acquisition

During childhood, learning is a critical component in the development of skilled movement behavior (Thelen, 1995). Neural maturation provides the possibility for movement, but it is through extensive practice and refinement of motor patterns that children develop skills comparable to those of adults in form and consistency. Recently, it has been proposed that a movement's form or topology emerges rapidly during early phases of skill acquisition (Gentile, 1998, 2000). Following Bernstein (1967), movement topology is viewed as the general spatial configuration or shape structure that remains relatively stable although the pattern may be scaled in amplitude, duration, or force. During early stages of skill learning, the performer develops a set of correspondences or mappings between his or her morphology and the environmental constraints, yielding a movement topology that successfully attains the task goal. Unlike topology, however, movement consistency has been proposed to develop gradually and to be evident only during later phases of skill learning (Gentile, 2000). Consistent movement requires the stabilization of an internal model of intersegmental dynamics that enables the control system to compensate for motion-dependent perturbations through feedforward control processes. Prolonged practice has been proposed as a necessary condition for gradual stabilization of that control model. Thus, it has been suggested that two interdependent processes are implicated in development of skill: one providing for the emergence of movement topology, the second mediating refinement of motor control. Those processes are proposed to operate in parallel but to affect performance changes at different rates as a consequence of practice.

Although young children can successfully carry out a wide range of everyday tasks, they are thought to be deficient in the extensive practice required to stabilize an internal model of intersegmental dynamics. In addition, as body morphology and moment of inertia for body segments change throughout childhood, the need for ongoing updating and refinement of the control model precludes its stabilization. We examined those suppositions in the present study by comparing movement form and consistency of young children with that of adults while they transitioned from sit to stand. Options for organizing an effective transition to standing are limited by physical constraints of the
support surfaces and by the body’s linked structure. Because young children can successfully transition from sit to stand, they were expected to display a movement form similar to that of adults. However, children were predicted to demonstrate high levels of within-participant variability in the movement patterns used for standing up.

Although the biomechanics of standing up in adults has been analyzed in several studies (Baer & Ashburn, 1995; Fleckenstein, Kirby, & MacLeod, 1988; Millington, Myklebust, & Shambes, 1992; Pai & Rogers, 1991), there have been few studies with children. In one recent study, Cahill, Carr, and Adams (1999) examined the sit-to-stand transition in children of various ages (12–18 months, 4–5 years, and 9–10 years). In general, movement form was similar across age groups and approximated the adult form reported in previous studies. However, the movement pattern was scaled differently because movement time, amplitude of trunk flexion, and peak angular trunk flexion velocity increased with age. Furthermore, younger children were found to be more variable than older children in movement time, onset of hip extension, and time to peak force. Because several of those kinematic measures increased in absolute value with age, Cahill and colleagues’ use of standard deviations instead of coefficients of variation as a measure of variability could have introduced a biasing artifact (the standard deviation increases with the absolute value of the mean). In addition, Cahill et al. (1999) did not examine the temporal coordination of segmental components. The timing and sequencing of segmental motion could provide important insights into the underlying control processes. Therefore, in the present study, we examined segmental temporal coordination as well as within-participant variability during the sit-to-stand transition performed by adults and children.

Although research on the sit-to-stand transition in children is limited, the form and variability of other movement patterns have been studied (Clark, Phillips, & Petersen, 1989; Frost, Dowling, Dyson, & Bar-Or, 1997; Hausdorff, Zemany, Peng, & Goldberger, 1999; Parker, Larkin, & Ackland, 1993; Robertson & Halverson, 1988). On the basis of qualitative descriptions of movement patterns, investigators believe that the adult form is achieved soon after initial success with a particular movement task. For example, VanSant (1988a, 1988b) found that 7-year-old children use patterns similar to those of adults in rising to stand from a supine position on the floor.

As demonstrated in several studies, prolonged practice appears to be needed before children achieve an adult’s level of movement consistency. Although the gait pattern approximates an adult form by 6 years of age (Sutherland, Olshen, Cooper, & Woo, 1980), Hausdorff et al. (1999) demonstrated that variability in the gait pattern decreases slowly with increasing age. They examined 3- to 14-year-olds and found that young children were highly variable in stride duration and did not approximate adult consistency until 11–14 years of age. Law, Gentile, and Bassile (1997) compared gait adaptations of 5- to 6-year-old children with those of adults as they stepped over obstacles during walking. The children displayed more variable toe trajectories than adults. Law and colleagues suggested that the young children had not stabilized an internal model of intersegmental dynamics and thus were unable to consistently compensate for motion-dependent torques while stepping over obstacles.

Variability in jumping and hopping is also greater in children than in adults. Clark, Phillips, and Petersen (1989) examined the standing long jump and the vertical jump in children and adults. Although the 3-year-old children were successful in propelling themselves off the ground by using a form similar to that of adults, the children displayed higher variability in joint angle and in jump height. Parker, Larkin, and Ackland (1993) reported decreasing within-participant variability with age (from 3 to 9 years) during one-foot hopping. Even the oldest children (8- to 9-year-olds) displayed more variability in that task than the adults did.

Sometimes, movement variability does not decrease linearly with age. Initially, the performer may use brute restrictions to decrease degrees of freedom, effectively limiting perturbations resulting from motion-dependent torques. In such cases, variability is reduced, but, as restrictions are released, it increases. For example, in a longitudinal study of hopping in children from 3 to 18 years of age, Robertson and Halverson (1988) found that young children initially freeze the arms and the contralateral leg, and only with increasing age are those limbs incorporated into the hopping maneuver. When the arms are incorporated into the hop, variability in the hopping leg increases. Not until children reach 15–18 years of age is consistency in the hopping pattern firmly established. Altogether, those earlier findings imply that when one uses age as a marker for experience, young children require considerable practice before consistent movement is achieved.

In the present study, we extended that line of investigation by examining movement form and consistency in 6- to 7-year-old children and adults during the performance of an everyday behavior: standing up. Transitioning from sit to stand is a functional developmental skill that places a number of biomechanical constraints on the performer. The performer has to deal with a changing base of support, moving the center of mass forward over the feet and upward through space, and either stopping in quiet standing or initiating locomotion. Although toddlers as young as 18 months can successfully perform that transition, we suggest that control of intersegmental dynamics required to cope optimally with those demands is not refined in young children. Thus, in the present study, two hypotheses were tested. First, we predicted that movement form would be similar for children and adults, reflecting their successful solution to the problem of standing up. Second, within-participant variability of various kinematic measures was predicted to be higher for children because they do not have optimal control of intersegmental dynamics.
Method

Participants

Six 6- to 7-year-old children (M = 6.6 years ± 4.2 months) and 6 adults (M = 27.9 ± 4.1 years) were recruited from the university and community as unpaid volunteers. All children were enrolled in age-appropriate-level classrooms. Children in learning disabled or special education classrooms were excluded. In addition, children and adults were excluded if they had a history of orthopedic, muscular, or neurological impairments. Informed consent was obtained from the adult participants and from the children’s parents or guardians, following standard guidelines. All children assented to participate in the study. The Committee for Research and Institutional Review at the University of Medicine and Dentistry of New Jersey approved the study’s protocol.

Task and Apparatus

Participants performed the sit-to-stand transition from a height-adjustable chair. Seat width was narrow enough to provide a stable surface but prevented the use of the arms to push up to the standing position. During two to four practice trials, participants selected a comfortable width between their feet. We then ensured that participants held that position constant over the trials by marking the floor with black tape posterior to their heel and along the lateral border of the foot.

We videotaped participants by using six 60-Hz cameras (Burle TC351A). Reflective markers were placed bilaterally on the following body landmarks: lateral aspect of the fifth metatarsal head, lateral malleolus, lateral femoral condyle, greater trochanter, seventh cervical (C7) spinous process (exception to the bilateral placement), midpoint of Frankfort plane (area between the tragus and the lowest point of the orbit), acromion, elbow lateral epicondyle, and midpoint (between radial and ulna heads) of dorsal wrist. We determined marker coordinates by using the Peak Motus three-dimensional system (Peak Performance Technologies, Englewood, CO). We performed data reduction by using the Peak Motus software program.

Procedure

Participants were required to wear shorts or bathing suits. Reflective markers were placed directly on the skin over bony landmarks (except for the metatarsal markers, which were placed on the shoe at the appropriate location). The chair height was adjusted for each participant so that the initial positions were hips 90° and knees 95° of flexion.

Participants were instructed to rise up from the chair at a comfortable speed without using their arms to push up to the standing position, to pause briefly, and to then return to the chair. Only the sit-to-stand portion was used for analysis. The participants started with their arms at their sides, but the arms were free to move during the transition. Carr and Gentile (1994) have reported that normal use of the upper extremity augments the force generation in the lower limbs. In addition, they found increased variability in this transition when the arms were restricted. Before each trial, the participant’s feet were positioned within the tape boundaries, hip and knee angles were checked, and the participants’ arms were positioned at their sides. The participants were provided with a verbal signal to go (“ready, set, go”). Data collection was started at the set command. Participants performed 10 repetitions of the sit-to-stand transition, with a brief pause between each trial.

Movement Analysis

Segmental angles were calculated in relation to the horizontal plane in a counterclockwise direction (Figure 1). Movement onset was defined as the time when segmental angular velocity of the trunk exceeded 5°/s. Movement was terminated when all segmental angular velocities were less than 2°/s. The lower cutoff for termination was chosen because it captured the end of segmental motion. For each segment, onset of flexion or extension was defined as the time when either segmental angular velocity exceeded 5°/s or angular velocity changed from flexion to extension (i.e., crossed the zero axis). Segmental motion was considered terminated when angular velocity changed direction from flexion to extension or was less than 2°/s.

For each segment, time spent in flexion and extension was calculated as a percentage of total movement time. However, percentage time to peak velocity was calculated with reference to the duration of the specific segmental motion (flexion or extension). As is demonstrated in Figure 2, we derived the onset-time differences by calculating the difference between the onset times (in percentage of total movement time) of two segments.
We assessed movement form by examining angle–angle plots of displacement at two segments, sequence of joint onsets, and proportional duration of segmental motion. We derived coefficients of variation (CVs) for each kinematic measure to evaluate movement consistency. The time lags in initiating motion at two segments (onset-time differences) were used as measures of temporal coordination.

Statistical Analysis

The following dependent variables were analyzed: (a) movement time; (b) proportional time spent in flexion and extension phases at the trunk, thigh, and shank; (c) onset times for each segment and onset-time differences for extension between two segments; (d) amplitude of segmental angular motion at the trunk, thigh, and shank; and (e) peak segmental angular velocity and proportional time to peak velocity for the trunk, thigh, and shank. For each variable, two scores were derived for statistical analyses: the mean and the CV. In addition to age groups, data were analyzed by phase of segmental motion (specifically, flexion and extension phases for trunk and shank and extension for the thigh). Thus, we conducted a 2 (age group) × 5 (segmental motion) analysis of variance (ANOVA) with repeated measures on the second variable. Omnibus tests were followed by use of the conservative Tukey’s test (HSD) for post hoc comparisons. The number of participants precluded the use of multivariate analysis. The probability level was .05 for all comparisons.

Results

General Form

Qualitative Description

The pattern for segmental angular displacement and velocity at the trunk, thigh, and shank was similar for adults and children (see Figure 3). The trunk initially flexed as it moved over the feet; it then extended as the body was propelled to the upright position. The thigh extended as the body moved off the seat, which occurred after initial flexion of the trunk and before initiation of trunk extension. The shank had two phases of motion, an initial flexion phase followed by an extension phase. Generally, the onset of shank flexion occurred at the same time as thigh extension, whereas shank extension began shortly after onset of trunk extension.
Segmental Angular Motion

Form was similar for children and adults, as represented by angle-angle plots of displacement at two segments, sequence of segment onsets, and proportional duration of segmental motion. For 1 representative child and 1 adult, angular displacement of thigh plotted against trunk and thigh plotted against shank (five superimposed trials for each participant) are shown in Figure 4. As can be noted, the angular displacement patterns have similar shapes for children and adults. In addition, adults demonstrated highly consistent coordination between the shank and thigh; children did not. The similarity of pattern was evident across all participants; variability was consistently higher for all children. The notable difference between children and adults was the presence of hooks in children’s thigh versus shank angular displacement plots. As shown in individual velocity profiles, the hooks reflected terminal adjustments necessary to attain a balanced position in standing.

Onset times were taken with reference to the initiation of trunk flexion and are reported as a percentage of total movement time (% MT). Shank flexion and thigh extension occurred first, at approximately the same time (children, 17.57% MT and 19.63% MT; adults, 14.13% MT and 13.37% MT, shank and thigh, respectively). Subsequently, trunk extension was initiated, followed by shank extension (children, 40.63% MT and 47.63% MT; adults, 47.17% MT and 49.27% MT, trunk and thigh, respectively).

As is evident in Table 1, the proportional duration of flexion or extension for segmental motion was significantly different between groups, $F(1, 10) = 20.278, p \leq .001, \eta^2 = .67$. As indicated in Table 1, both thigh and shank extension were significantly longer for adults ($p \leq .01$ and $p \leq .05$, respectively). Trunk flexion averaged about 40% MT and trunk extension about 52% MT. Those percentages do not add to 100% MT because trunk motion terminated earlier than did that of the other segments on some trials. Additionally, there was a segment effect, $F(4, 40) = 89.277, p \leq .001, \eta^2 = .90$. 
The thigh has only one direction of motion, therefore thigh extension was significantly longer in proportional duration than were the extensions of all other segments. In addition, trunk and shank extension were significantly longer than were their respective flexion components, indicating that more time was spent in rising to the standing position.

Regarding angular velocity, there was a significant effect of group, $F(1, 10) = 5.657, p \leq .05, \eta^2 = .36$, and a Group X Segment interaction, $F(4, 40) = 3.194, p \leq .05, \eta^2 = .24$. Post hoc analysis indicated that children’s shank flexion and thigh extension velocities were significantly higher than adults’. Across segments, angular velocity was higher for thigh extension than for trunk flexion in children but not in adults (Table 1).

There were no statistically significant group effects for maximum angular displacement or proportional time to peak velocity. Segment effects were found for those measures, however, $F(4, 40) = 97.751, p \leq .001, \eta^2 = .91$, and $F(4, 40) = 9.047, p \leq .001, \eta^2 = .48$, respectively. For maximum angular displacement, trunk and shank flexion were significantly less than extension because of biomechanical limitations in moving the body forward over the feet. Proportional time to peak velocity occurred significantly earlier for trunk and shank extension than for their respective flexion phases.

**Variability**

**Qualitative Description**

The phase-plane plots (five superimposed trials for each participant) of angular velocity and angular displacement for both the trunk and the shank for 1 representative child and 1 adult are shown in Figure 5. The sit-to-stand movement started with flexion at both segments that increased in velocity as the transition progressed. Motion at those segments continued smoothly into extension as the flexion velocity reached zero and the angle began to increase. Children were more variable than adults at both segments. With the overall pattern, adults were most consistent at initiation and termination of the transition. In contrast, children demonstrated high variability throughout the transition. In addition, children displayed secondary adjustments (i.e., the
| TABLE 1. Means and Mean Coefficients of Variation for Peak Angular Displacement and Velocity, Onset, and Duration of Segmental Angular Motion |
|-------------|-----------------|-----------------|-----------------|-----------------|
| Segment motion | Mean | Mean | Mean CV | Mean CV |
| | Children | Adults | Children | Adults |
| | M | SD | M | SD | M | SD | M | SD |
| Movement time (s) | 1.48 | .15 | 1.58 | .13 | .10 | .04 | .09 | .04 |
| Duration (% MT) | | | | | | | |
| Trunk flexion | 40.63 | 1.7 | 41.30 | 7.0 | .13 | .07*** | .06 | .03 |
| Shank flexion | 30.07 | 5.6 | 35.13 | 4.9 | .18 | .02*** | .10 | .03 |
| Thigh extension | 74.03 | 4.9** | 83.10 | 6.8 | .10 | .05 | .05 | .01 |
| Trunk extension | 53.77 | 5.0 | 51.87 | 5.9 | .14 | .06*** | .07 | .03 |
| Shank extension | 39.03 | 6.9* | 48.10 | 8.9 | .18 | .08*** | .08 | .04 |
| Peak angular velocity (deg/s) | | | | | | | |
| Trunk flexion | 102.23 | 17.0 | 88.55 | 6.7 | .12 | .06 | .11 | .03 |
| Shank flexion | 44.61 | 13.8* | 25.94 | 5.7 | .22 | .16 | .21 | .10 |
| Thigh extension | 135.31 | 34.7** | 100.89 | 17.0 | .13 | .06 | .06 | .03 |
| Trunk extension | 64.58 | 14.3 | 65.44 | 9.5 | .24 | .08 | .13 | .05 |
| Shank extension | 43.49 | 10.8 | 33.23 | 4.8 | .28 | .12 | .15 | .13 |
| Proportional time to peak velocity | | | | | | | |
| Trunk flexion | 55.9 | 8.5 | 59.6 | 10.6 | .15 | .09 | .11 | .08 |
| Shank flexion | 57.9 | 6.3 | 56.1 | 3.2 | .16 | .07 | .08 | .04 |
| Thigh extension | 54.2 | 2.6 | 47.2 | 8.4 | .17 | .10** | .07 | .03 |
| Trunk extension | 46.2 | 4.7 | 38.1 | 7.4 | .25 | .07*** | .09 | .03 |
| Shank extension | 51.4 | 6.6 | 45.7 | 11.7 | .20 | .07 | .14 | .09 |
| Peak angular displacement (deg) | | | | | | | |
| Trunk flexion | 53.39 | 4.2 | 54.22 | 8.8 | .09 | .05 | .06 | .05 |
| Shank flexion | 66.77 | 5.1 | 67.11 | 4.2 | .04 | .02 | .03 | .02 |
| Thigh extension | 76.00 | 8.8 | 82.88 | 2.8 | .06 | .06 | .01 | .01 |
| Trunk extension | 84.51 | 3.1 | 86.86 | 2.1 | .03 | .01 | .02 | .01 |
| Shank extension | 81.87 | 4.6 | 82.07 | 2.8 | .03 | .01 | .02 | .02 |
| Onset time differences (% MT) | | | | | | | |
| Sh flex – Tr ext | 23.07 | 7.5 | 27.30 | 3.4 | .33 | .14*** | .13 | .03 |
| Th ext – Tr ext | 21.00 | 3.9** | 28.07 | 4.4 | .24 | .15** | .12 | .06 |
| Tr flex – Tr ext | 40.63 | 1.7* | 47.17 | 2.1 | .13 | .07 | .05 | .02 |
| Th ext – Sh ext | 28.00 | 3.4** | 35.90 | 6.5 | .19 | .07 | .10 | .03 |

Note. Children versus adults *p < .05. **p < .01. Abbreviations: SD = standard deviation; CV = coefficient of variation; % MT = percentage of total movement time. Proportional time to peak velocity = % of duration of segmental motion (flexion or extension). Onset-time differences: Th ext – Tr ext = time of thigh extension initiation minus time of trunk extension initiation. Tr = trunk, Th = thigh, Sh = shank, ext = extension, flex = flexion.

hooks described previously) that occurred at the shank after velocity had reached the termination threshold. Those secondary adjustments were observed on 21 of the 30 trials for the children but were not seen on any trial for adults. The velocity of the submovements ranged from 4°/s to 16°/s.

Segmental Angular Motion

As shown by mean CVs in Table 1, children were more variable than adults in duration and proportional time to peak velocity. Overall, group effects were significant for duration,
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$F(1, 10) = 78.086, p \leq .001, \eta^2 = .89$, and for proportional time to peak velocity, $F(1, 10) = 17.405, p \leq .05, \eta^2 = .64$. Post hoc comparisons indicated that children were more variable than adults on both trunk and shank duration measures for flexion and extension phases. In addition, there was a segment effect: Shank flexion duration was significantly more variable than thigh extension duration ($p \leq .05$). In terms of proportional time to peak velocity, thigh and trunk extension were more variable for children than for adults.

The mean CVs for angular displacement tended to be higher for children than for adults, but differences only approached statistical significance ($p \leq .06$). Segment effects were found, $F(1, 10) = 7.429, p \leq .001, \eta^2 = .43$. Angular displacement of trunk flexion was significantly more variable than were shank or thigh motion. Thus, both groups were least consistent in the degree of forward trunk displacement in comparison with the degree of displacement of all other segments.

No significant group differences were found for angular velocity CVs, but a segment effect was noted, $F(1, 10) = 8.567, p \leq .001, \eta^2 = .46$. Across segments, shank was most variable, thigh least. Thus, variability significantly increased at the distal segment, which may have resulted from motion-dependent torques.

Temporal Coordination

Onset-time differences were smaller for children than for adults, as shown in Table 1, $F(1, 10) = 11.810, p \leq .01, \eta^2 = .54$. Specifically, children had briefer time lags than did adults between thigh extension and trunk and shank extension and between trunk flexion and trunk extension. In addition, an overall segment effect was found, $F(3, 30) = 75.095, p \leq .001, \eta^2 = .88$, which was primarily caused by the order of onsets, with the longest lag occurring between trunk flexion and trunk extension.

Variability for onset-time differences was higher for
children than for adults (Table 1), as indicated by the significant group effect, \( F(1, 10) = 15.804, p \leq .01, \eta^2 = .61 \). Although children were more variable than adults on all CVs for onset-time differences, conservative post hoc comparisons indicated significant contrasts between the age groups for the intervals between shank flexion and trunk extension and between thigh extension and trunk extension. In addition, there was a segment effect, \( F(3, 30) = 7.376, p \leq .001, \eta^2 = .42 \), indicating that the temporal lag between shank flexion and trunk extension was significantly more variable than were the lags between thigh motion and extension at the trunk or shank. The termination of shank flexion and the onset of trunk extension are important to limiting the forward motion and bringing the trunk to the upright position.

**Discussion**

In performing the sit-to-stand transition, young children displayed more variable movement patterns than adults did. As shown by coefficients of variation for duration, proportional time to peak, and onset-time differences, children's variability measures tended to be twice those seen for adults. In contrast, movement form was similar for the two age groups, as evidenced by sequence of joint onsets, proportional duration of segmental motion at trunk and shank flexion, and angle–angle segmental displacement plots. Those findings provide support for our predictions concerning movement form and consistency. Although children have developed an adult-like form leading to success in standing up, they do not have refined motor control processes required for consistent movement.

Because success in standing up typically occurs around 18 months of age, these young children have repeatedly performed that everyday task over a period of several years. Thus, the young child's lack of movement consistency implicates a learning process that changes very gradually as a consequence of practice. That process is presumed to involve acquiring and stabilizing an internal model of intersegmental dynamics.

The achievement of optimal control of the dynamical system allows a performer to predictively compensate for motion-dependent perturbations, leading to smooth and consistent movements. Although prolonged practice enables the young child to develop a control model adequate for successful performance, stabilizing that dynamical model may be difficult as body morphology changes throughout childhood. There is an accelerated growth period, the midgrowth spurt (Gasser et al., 1991), which occurs in children around 6 to 7 years of age. Marked changes in the inertial characteristics of body segments during that age range would require ongoing updating and refinement of an internal control model. As shown by Shumway-Cook and Woollacott (1985), 4- to 6-year-olds demonstrate higher variability in timing and amplitude of postural synergies during platform perturbations than do toddlers or 7- to 10-year-old children. However, in spite of possible alterations in body morpholo-

gy resulting from the midgrowth spurt, the young children in the present study displayed a movement form comparable with that of adults. That finding implies that acquisition of movement topology—the mapping between body morphology and environmental constraints yielding successful goal attainment—is distinct from the learning processes linked to the control of intersegmental dynamics that yields movement consistency. Recently, Krakauer, Ghitardi, and Ghez (1999) reached a similar conclusion on the basis of a study of adults acquiring a reaching task under novel transformations. They produced evidence supporting the concept of two parallel but independent learning processes: one associated with acquisition of a kinematic model, the second linked to learning a model of intersegmental dynamics.

Our finding that children stabilize the movement's form before attaining movement consistency concurs with previous reports on sit-to-stand (Cahill et al., 1999) and other developmental skills, such as gait (Frost et al., 1997; Hausdorff et al., 1999, Law et al., 1997) and jumping (Clark et al., 1989; Parker et al., 1993). As discussed by Thelen (1995), the young child first explores movement configurations that "get into the ball park" (Green, 1972, p. 328), leading to initial and tentative success in a task. With the narrowing of possible forms through selection processes, a stable configuration emerges that must be "tuned" through practice so that smooth and efficient movement can be achieved. Similarly, Manoel and Connolly (1997) have suggested that young children first develop the movement's macrostructure, and they then refine its microstructure during later phases of skill learning. Research on skill acquisition during infancy has provided support for those proposals. For example, studies of infants' reaching have shown that hand trajectories leading to initial success in contacting an object are characterized by segmented velocity profiles and irregular paths (Konczak, Boruttas, & Dichgans, 1995; Konczak, Boruttas, Topka, & Dichgans, 1995; Konczak & Dichgans, 1997; Thelen et al., 1993). With ongoing practice, those crude trajectories become somewhat smoother as the infant gains some control over intersegmental dynamics (Konczak, Boruttas, & Dichgans, 1995; Konczak, Boruttas, et al., 1995; Konczak & Dichgans, 1997). However, the young child's reaching movements do not attain the consistency or approximate the stereotypic patterns displayed by adults until almost 3 years of age. As demonstrated by Konczak et al. (1997), young children require practice over that extended period of time to effectively exploit reactive forces and to appropriately time active force production.

In the present study, we also found that children's timing of segmental motion appeared inconsistent and inefficient. As shown in the analyses of CVs, children displayed higher variability than adults did on those measures that reflect the timing of the transition from forward motion to erect standing (duration, proportional time to peak for thigh and trunk extension, and onset-time differences). In addition, the mean time lags between onset of thigh and trunk extension and thigh and shank extension differed for children and
adults. During trunk flexion, adults appeared to time initiation of thigh extension to optimize transfer of upper-body momentum to the rising component in standing up (Schenkman, Berger, Riley, Mann, & Hodge, 1990). Schenkman and colleagues proposed that forward momentum of the trunk facilitates lower limb extension and reduces the active muscle force required. Although the sequence of joint onsets was similar to that of adults, children’s timing of thigh extension appeared to limit momentum transfer. In comparison with adults, children tended to delay onset of thigh extension and initiate trunk and shank extension slightly sooner. As a consequence, children had significantly briefer time lags between initiating thigh and trunk extension and between thigh and shank extension. The briefer time lags appeared to limit exploitation of momentum transfer and to increase the requirement for active force production in generating vertical momentum. In previous research with adults, time between thigh and trunk extension was observed to shorten and even reverse when investigators limited momentum transfer by having participants stand up from a starting position of partial or full trunk flexion (Shepherd & Gentile, 1994).

An additional finding supports our interpretation that children did not fully exploit momentum transfer. Peak velocity for thigh extension and shank flexion was higher and percentage time to peak for trunk and shank extension occurred sooner in children than in adults. The absence of force plate or electromyographic data and the small number of participants in the present study limits our interpretation; however, present findings imply that the children’s rapid extension at the thigh generated more active vertical momentum than was evident in adults. That rapid and forceful extension also appeared difficult to control as children made secondary adjustments of the shank before achieving quiet standing. Overall, those differences in temporal coordination seemed to reflect the same underlying process that gives rise to children’s higher movement variability, that is, the inability to optimally control intersegmental dynamics.

In summary, 6- to 7-year-old children in the present study displayed a movement form in the sit-to-stand transition that was comparable with that of adults. However, the children’s movement was less consistent, and their momentum transfer appeared less efficient. We interpret those differences as a reflection of inadequate control of intrinsic dynamics. We assume that refinement of an internal dynamical model develops very slowly with practice and requires ongoing updating as body morphology changes. Thus, more extended practice and relative stabilization of body structure is necessary before young children can attain the adult’s level of consistency and efficiency.

ACKNOWLEDGMENTS

Special thanks to all the volunteers who participated in this study and to the faculty and students at the University of Medicine and Dentistry of New Jersey, Physical Therapy Program and the Teachers College Motor Learning Program for their support and assistance during this research project.

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Submitted February 25, 2002
Revised March 26, 2003