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Changes in Mechanical Control of Movement During the First 5 Months of Independent Walking: A Longitudinal Study

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ABSTRACT. Insight into neuromuscular control of movement is gained through an understanding of the mechanical causes of movement. Data on new walkers' net joint moments is scarce, however, although those moments can be considered the direct cause of movement. The authors' goal in this research project was to characterize net joint moments in toddlers (N = 10) during the first 5 months of independent walking and to discuss their role in mechanical control of walking. The authors modeled leg segments as oscillating pendulums fixed at the proximal joint and investigated the relationship between force and movement. Their investigation revealed that at the onset of independent gait, walking was primarily hip driven. Furthermore, the toddlers seemed to experience problems in uncoupling active and passive control around the joints. Changes in mechanical control of walking were observed after 3 to 4 months of independent walking. The changes were more obvious at the hip and the knee joint than at the ankle.

Key words: coordination, dynamical systems approach, gait, neuromechanical control, toddler

Development of a movement skill is viewed as a process of change within a complex dynamical system—in this study, the child (Smith & Thelen, 2003; Thelen, 1995). From that point of view, motor development is considered to be a multifactorial evolution. The sequence of motor milestones acquired during the first 2 years of life is seen as a sequence of different stages in an epigenetic landscape (Smith & Thelen). The acquisition of sitting, crawling, standing, and walking can be considered as a series of evolving and dissolving patterns, during which the process of change is governed by constraints in the individual, in the task, and in the environment. In particular, the capability of the human brain to cope with ongoing individual and environmental changes is essential for development (Metta, Sandini, & Konczak, 1999). A combination of neuromaturation and physical growth are thought to lead to improvements in postural control and movement coordination and to an increase in muscle force. In addition to the impact of gravity on the mechanics of control, environmental factors are important in creating opportunities for practice.

Variability is an inherent feature of the process of motor development and is linked to the redundancy of the motor system, and there are many plausible kinematic movement patterns for performing the same task (see Sporns & Edelman, 1993). During development, variable movement patterns allow the child to explore many possible solutions for a given task (Thelen, 1995). Purposeful movements will be reinforced (Sporns & Edelman) and are more likely to be performed again in a future similar situation. Emergence of coordinated movements depends both on musculoskeletal growth and neural maturation. Therefore, insight into the biomechanics of movement is essential for understanding development (Sporns & Edelman).

Independent walking is one of the motor skills that is thought to be very important in normal motor development. Walking is the first to evolve in a series of fundamental movement skills (Clark & Whitall, 1989) and may be considered a prerequisite for learning to run, gallop, hop, and skip. When children master the skill of walking, they gain independence, while their hands are free for other tasks (Adolph, Vereijken, & Shrout, 2003). Furthermore, independent ambulation is a necessary condition for normal social, behavioral, and even cognitive development (Thelen, 1995).

In their studies of the early development of independent walking in toddlers, researchers primarily focused on inter-

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limb and intralimb coordination. They tried in that way to answer the question of how infants are able to combine the numerous degrees of freedom of a moving body to achieve a low-dimensional behavior such as walking. Clark (1995; Clark & Phillips, 1993; Clark, Whitall, and Phillips, 1988) showed that the legs and the leg segments during walking could be modeled as coupled oscillators that are attracted to a certain phasing relationship. Interlimb coordination on average showed a 50% phasing relationship from the onset of independent walking on. However, variability was large, and it decreased to adult-like values only after approximately 3 months of walking experience.

Their research also showed that the thigh and shank could be modeled as limit-cycle oscillators, fixed at the knee joint. The phase plot (angular displacement plotted vs. angular velocity) of each segment was highly variable at the onset of independent walking, showing that the attractor state was weak. After 3 months of walking experience, an attractor state that resembled the limit cycle observed in adults could be defined. The relative phasing relationship between thigh and shank was also highly variable at the onset of independent walking. Again, after 3 months of independent walking, the relative phase lag showed a smoother but nonlinear relationship that more closely resembled the adult pattern.

Investigators have proposed different potential control parameters as factors that limit the onset of independent walking, for example, immature postural control, limited muscle strength, and immature movement coordination and control (Thelen, 1995). The data of Clark and Phillips (1993) provided support for those proposals. They showed that support (effect on postural control) and weighting of the leg (requires more muscle strength) altered the inter- and intralimb coordination patterns. Ivanenko, Dominici, Cappelini, Dan, and Cheron (2004) showed that immature movement coordination influences center of mass movements and makes walking in toddlers more energy demanding. Apart from the constraints posed by Thelen, anatomy and morphology may also play an important role in determining the outcome of motor development. Bertsch, Unger, Winkelman, and Rosenbaum (2004) showed that during the first year after the onset of independent walking, foot loading is largely influenced by changes in foot shape.

Previous researchers have emphasized the need to provide a detailed description of the gait pattern in toddlers. However, the use of only kinematic data limits one's ability to understand the emergent control of developmental skills. The first step toward more insight into neuromuscular control of movement is to improve our understanding of the mechanical causes of movement (Frigo, Crenna, & Jensen, 1996; McFadyen, 1994). Net joint moments reflect the net summation of all muscular and nonmuscular forces at each joint and can be considered to be the direct mechanical causes of movement. Until recently, joint kinetic data were available only for children over 3 years old. During the past 4 years, we were able to perform a longitudinal follow-up study characterizing net joint moments and power output at the lower extremity joints in children during the first 5 months of independent walking (Hallemans, De Clercq, & Aerts, 2006; Hallemans, De Clercq, Otten, & Aerts, 2005). In the present study, we examined the coupling between the net joint moment and the angular displacement at the joint by using moment–angle plots. Information such as that can help us to directly understand mechanical control mechanisms implemented by the toddler (Frigo et al., 1996). The use of moment–angle plots in investigating the coupling between force and movement has the advantage of providing us with a visual representation of mechanical control of movement. For example, the moving leg segment can be modeled as an oscillating pendulum. If the movement of that pendulum is entirely driven by active force production around a joint (active control of movement), then the moment–angle plot resembles a closed orbit turning clockwise. If the movement of the segment is slowed down by the muscles spanning the joint (passive control of movement), then the orbit would turn counterclockwise. In addition, the area enclosed by the orbits provides insight into the absorption and generation of power (Frigo et al.).

Our goal in the present study was to investigate the mechanical control strategies of walking in toddlers' gait. To do so, we modeled the moving leg segments as oscillating pendulums fixed at the proximal joint. We looked at the thigh, the shank, as well as the foot. Changes in mechanical control strategies over the first 5 months of independent walking were investigated. According to the dynamic view of development, we expected the moment–angle plots to be highly variable in shape at the onset of independent walking but to decrease in variability with developmental time. We considered both interindividual and intraindividual variabilities.

Materials and Method

Participants

We followed 10 children intensively during the first 5 months after the onset of independent walking. Gender, term, birth weight, and the age of onset of walking of the study participants can be found in Table 1. The children came to the gait laboratory for the first time within a week after the onset of independent walking. We defined *onset of walking* as the ability to perform three consecutive steps. Subsequent recording sessions were performed after approximately 2, 3, 4, 6, 8, 10, 12, 16, and 20 weeks of walking experience. Because of illness, holidays, or unwillingness to cooperate, 9 of the children missed one or more recording sessions. The points of data collection in which data are missing are shown in Table 2. Nine of the 10 participants missed one or more data sessions. Because we observed little change in the gait pattern over 1 month of independent walking, we grouped the data for analysis per month of walking experience, leading to the

TABLE 1. Detailed Information About the Study Participants

No.	Gender	Pregnancy (weeks)	Birth weight (kg)	Age at first steps (months)
1	Female	40	3.44	10.0
2	Male	40	2.66	13.0
3	Female	40	3.79	12.0
4	Female	41	3.41	14.0
5	Female	39	3.66	11.0
6	Female	38	3.65	15.0
7	Female	40	3.55	11.0
8	Male	38	3.08	14.0
9	Male	38	3.00	14.5
10	Female	42	3.98	12.0

following distribution of data: onset of independent walking, 1st month (combining data from Weeks 2, 3, and 4), 2nd month (data from Weeks 6 and 8), 3rd month (data from Weeks 10 and 12), 4th month (Week 16), and 5th month (Week 20). The grouping of the data increased the number of trials per group and limited problems with missing sessions.

All participating children had to be full-term and of normal birth weight, and they had to have followed the normal time path for cognitive, language, motor, and social development. We obtained information on those issues from a questionnaire and a standard developmental test (Denver Development Screening Test; Barnes & Stark, 1975). Parents gave written consent to participate. The Ethical Committee of the University of Antwerp approved the study protocol, and we performed the research according to the guidelines stated in the Declaration of Helsinki.

Experimental Setup

Detailed information about the experimental setup and methods of data acquisition can be found in previous publications (Hallemans, Aerts, Otten, De Deyn, & De Clercq, 2004; Hallemans, De Clercq, & Aerts, 2005; Hallemans, De Clercq, Otten, et al., 2005). In short, the experimental setup consisted of a wooden walkway (1.5 m $\times$ 3 m) in which two 0.4 $\times$ 0.5 m force platforms (AMTI, Watertown, MA) were built. The walkway was surrounded by six infrared video cameras (Vicon Mcam 60, 250 Hz; Oxford, England) that enabled us to track the movements of the children. We used an adjusted version of the Helen-Hayes marker setup (Figure 1). We encouraged the children to walk several times over the platform at self-selected speed. We usually obtained three to four good trials . Selection criteria for good trials were as follows: (a) Only the toddlers feet were on the recording platform (with one foot touching each force plate), (b) all markers were visible throughout the trial, and (c) the trial was dynamic (i.e., trials in which the toddler fell, stopped, or turned were not incorporated in the analysis). The number of successful trials per session and the average number of steps per trial are shown in Table 2. From each successful trial we chose one representative gait cycle for further analysis. We normalized gait cycles to 100%. We obtained kinematic (three-dimensional joint angles) and kinetic (net joint moment profiles) data by using the Vicon Clinical Model (VCM; Davis, Ounpuu, Tyburski, & Gage, 1991; Grood & Suntay, 1983; Kadaba, Ramakrishnan, & Wootten, 1990). Joint angles and net joint moment time profiles have been discussed elsewhere (Hallemans et al., 2005).

TABLE 2. Successful Number of Trials for Each Child for Each Month of Walking Experience

	Trials (Steps)									
	1 week	1st month			2nd month		3rd month		4th month	5th month
Child	Onset	2 wks	3 wks	4 wks	6 wks	8 wks	10 wks	12 wks	16 wks	20 wks
1	5 (5)	4 (6)	5 (7)	5 (7)	NA (14)	NA (7)	5 (5)	5 (5)	2 (6)	5 (9)
2	3 (7)	3 (10)	—	—	—	4 (8)	3 (5)	4 (5)	4 (6)	3 (7)
3	—	—	—	4 (8)	3 (8)	2 (7)	—	—	4 (6)	3 (5)
4	—	4 (13)	5 (8)	4 (7)	5 (8)	4 (9)	—	5 (6)	5 (6)	5 (7)
5	2 (9)	5 (12)	–	4 (7)	2 (5)	5 (10)	4 (8)	4 (8)	2 (9)	—
6	5 (8)	4 (7)	5 (6)	—	5 (7)	5 (7)	5 (7)	5 (6)	—	3 (5)
7	1 (6)	3 (7)	4 (5)	5 (12)	3 (8)	5 (6)	5 (7)	5 (7)	3 (7)	4 (7)
8	2 (5)	3 (6)	—	5 (9)	4 (7)	3 (6)	4 (5)	5 (7)	4 (6)	3 (5)
9	—	—	5 (10)	—	4 (6)	3 (5)	3 (5)	4 (6)	4 (4)	3 (5)
10	3 (5)	5 (6)	2 (7)	5 (> 5)	5 (> 5)	4 (> 5)	3 (> 5)	3 (> 5)	3 (> 5)	4 (> 5)

Note. The average number of steps per trial that were in view of the cameras is shown between parentheses. The number of steps per burst that was selected for analysis was counted and was then averaged. A *burst* was defined as the portion of the trial during which the toddler walked without stopping, turning. or sitting down. NA = not analyzed; those trials had insufficient visible markers and therefore could not be analyzed. Dash (—) = no data were available.

FIGURE 1. The Helen-Hayes marker set was used for measuring full-body kinematics. Markers were attached to a tight-fitting suit because the children did not put up with markers stuck on their skin. Joint angles are expressed as Cardan angles of the more distal to the more proximal segment over the *x*-, *y*-, and *z*-axes, representing adduction–abduction, flexion–extension, and interior–exterior rotation. Angles are zero when standing upright, as shown here.

Data Analysis

Moment–angle plots. To gain more insight into the mechanical control mechanism of walking, we investigated the relationship between the net force that drives the pendulum (net joint moment) and the observed movement. Therefore, we plotted net joint moments around the hip, knee, and ankle (obtained from the VCM) relative to the angular displacement of the thigh, shank, and foot segments (expressed relative to the more proximal segment: thigh vs. pelvis, shank vs. thigh, and foot vs. shank). If the pendular movement of the thigh, shank, and foot depends only on active muscle force production at the proximal joint, we would expect to see a closed periodic orbit turning clockwise. In adults, we know that is not the case, and shifts are observed between periods of active (power generation, clockwise loop) and passive (power absorption, counterclockwise loop) control of movement (Frigo et al., 1996). We described the shapes of the moment–angle plots in the toddlers for the different walking ages, and we expected important changes with increasing walking experience because we know from kinematic data that important changes occur in intralimb coordination.

We chose to investigate both the average patterns as well as the individual differences. We obtained average patterns by first averaging the different numbers of successful trials per individual. Then, we again averaged individual averages to obtain the global average pattern for that recording session. Although inspection of average patterns enables one to identify global maturational trends, valuable information on intraindividual variation might be lost. Therefore, we also looked at the individual moment–angle plots for each session.

Variability of the moment–angle plots. We calculated a within-participants ratio of variability (RV_{wi}) to quantify the overall deviation of the time profiles of different gait cycles from the average. To obtain RV_{wi}, we first averaged elevation angles and net joint moment time profiles for each individual in each recording session and calculated a standard deviation SD_i from that average for each data point in the gait cycle. Then, we averaged the SD_is over the entire gait cycle. To obtain a ratio, we divided the average *SD* by the signal range.

To quantify interindividual variability, we calculated a between-participants ratio of variability (RV_{bw}) on the session averages for the joint angles and net joint moment. We calculated RV_{bw} by averaging the *SD*s of the average time profile over the entire gait cycle and dividing it by the signal range.

Using a regression analysis, we statistically tested changes in RV_{wi} and RV_{bw} with increasing walking experience (expressed in months) in Sigmaplot (Version 8.02 for Windows). We averaged the individual values of RV_{wi} per session to prevent problems of pseudoreplication. For RV_{bw}, only one value per session was available. Most developmental parameters, including movement skills (Adolph et al., 2003), show a negatively accelerated relationship with respect to developmental time. Therefore, we chose to model the expected decrease in interparticipant and intraparticipant variabilities by using an exponential decay model: $RV = y_0 + a*e^{-b*\mathrm{WE}}$. We expressed walking experience (WE) in months after the onset of independent walking. The use of an exponential model gave us the possibility of determining a time constant of change ($\tau = 1/b$). We estimated model parameters (the intercept y_0, the factor a, and the exponent b, according to that equation) in Sigmaplot by using a weighted regression analysis. We tested the significance of the obtained relationship by using an analysis of variance (F test). We set the significance level at .05.

Results

Moment–Angle Plots

Figures 2–4 show the average moment–angle plots for different walking ages. Individual graphs of one representative individual are also shown to give an idea of the amount of interparticipant and intraparticipant variation (we chose Participant 10 because those data were available for all recording sessions).

Around the Hip Joint

In the adults, the moment–angle plot around the hip joint (Figure 2A) typically showed two loops: one clockwise (around foot contact, representing power generation) and one counterclockwise (around toe-off, representing power absorption). In the toddlers at the onset of independent walking, individual variation was extremely large. On average, only one clockwise loop could be identified (Figure 2B). That finding indicates that the oscillating movement of the thigh completely depends on active muscle force production, leading to power generation. An average pattern with two loops (one clockwise and one counterclockwise) could be identified after only 4 months of walking experience (Figure 2E). But the orientation and size of the loops still differed from what we observed in adults. During the 5th month of walking experience, we observed a developmental reversal toward the immature pattern with only one closed orbit turning clockwise (Figure 2F).

Around the Knee Joint

Two counterclockwise loops (power absorption) characterized the moment–angle plot around the knee joint in the adults. The first loop was observed shortly after foot contact, and it reflected the shock-absorbing flexion–extension wave. The second loop occurred around toe-off, and it represented absorption of energy as knee flexion slowed down during terminal stance and early swing (Figure 3A).

The shape of the moment–angle plot around the toddlers' knee was very irregular. On average at the onset of independent walking, only one counterclockwise loop could be observed (Figure 3B). The loop during stance was very flat, and power was largely absorbed during swing. The movement of the shank seemed to be passively controlled. Changes were observed in the average knee moment–angle plot after approximately 3 months of walking experience (Figure 3D). A small counterclockwise loop emerged following foot contact. That finding shows that the knee became important in shock absorption at foot contact. That loop appeared gradually, but often it remained small. Moreover, the second loop that occurred around toe-off was very small.

Around the Ankle Joint

In the adults, there was a very small counterclockwise loop around the ankle (power absorption during the first rocker, i.e., foot roll-over) and a large clockwise loop, representing power generation in the ankle for push-off (Figure 4A).

In the toddlers, the moment–angle plots around the ankle were extremely variable. The average patterns usually showed a small and irregular clockwise loop, representing a small amount of power generation around the ankle for push-off (Figure 4B). When inspecting the average moment–angle plots, one cannot see a clear maturational trend.

Variability in Mechanical Control of Movement

To investigate the dynamical stability of mechanical control strategies adopted by each individual, we calculated *RV*s for the angular displacements of the thigh, shank, and foot segment, and net joint moment profiles around the hip, knee, and ankle. We looked at interindividual and intraindividual variabilities (RV_{bw} and RV_{wi}, respectively). RV_{wi} and RV_{bw} for different walking ages are shown in Figures 5 and 6. On average, RV_{wi} was much smaller than RV_{bw}, especially at the onset of independent walking.

Look first at the changes in RV_{wi} in movement kinematics and kinetics with developmental time (Figure 5). The RV_{wi}s for the elevation angles of the thigh, shank, and foot were relatively large at the onset of independent walking (between 30% and 40%). Variations in thigh angle and shank angle showed a significant decrease with increasing WE ($p < .05$). The results of the exponential decay model are shown in Table 3. After approximately 1.5 to 1.8 months of independent walking, RV_{wi} in movement kinematics

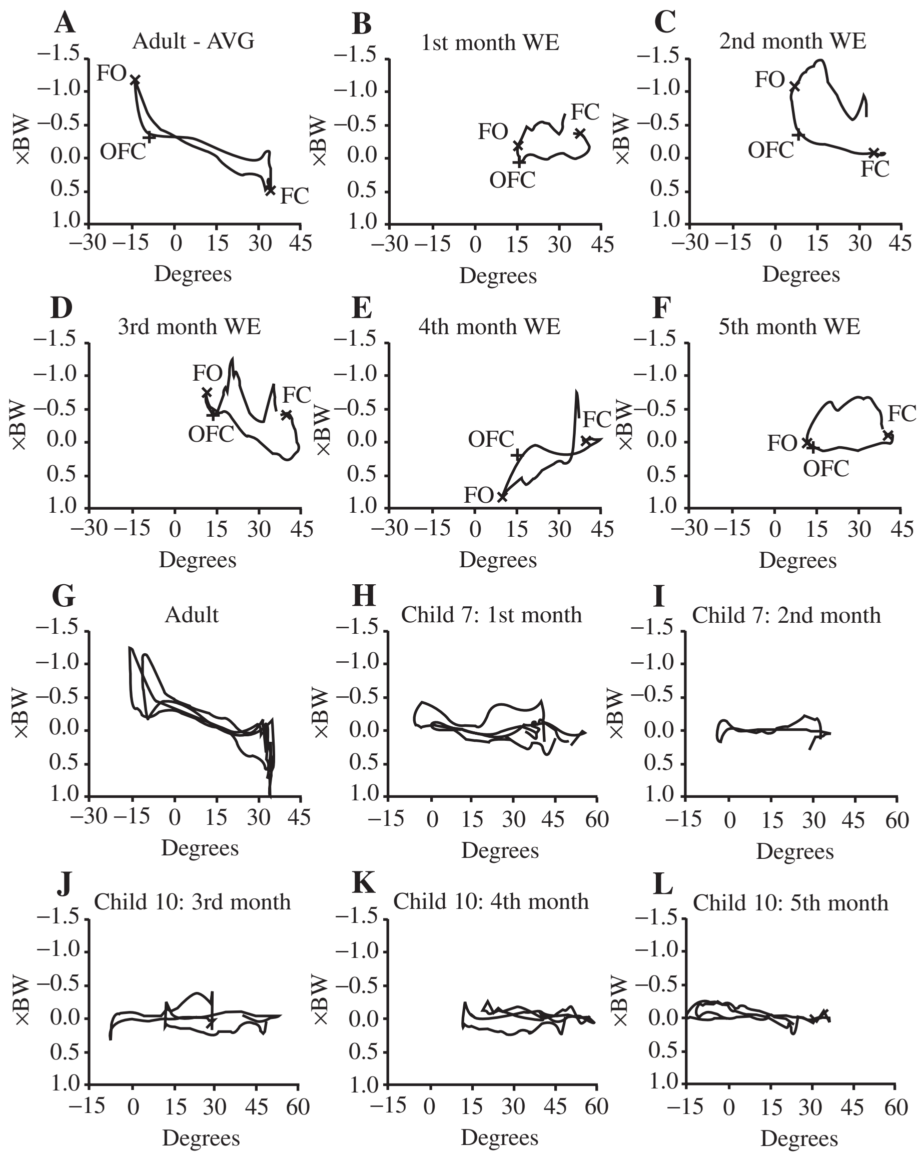

FIGURE 2. Moment–angle plots for the hip joint of adults compared with those of toddlers at the onset of independent walking (1st month) and after 2, 3, 4, and 5 months of walking experience (WE). (**A** to **F**) The session averages. On the average profiles, the instances of foot contact (FC), opposite foot contact (OFC), and foot off (FO) are indicated. (**G** to **L**) The different gait cycles from the same individual plotted on top of each other so that one can see the repeatability of movement control. BW = body weight.

decreased to an average of below 10%. The RV_{wi}s for the hip, knee, and ankle moments were moderately large at the onset of independent walking (between 20% and 35%) and showed no relationship with developmental time.

We also considered changes in RV_{bw} in movement kinematics and kinetics (Figure 6). The RV_{bw}s for the elevation angles of the thigh, shank, and foot were large at the onset of independent walking (between 25% and 60%) and showed no change with increasing WE. The RV_{bw}s for the hip, knee, and ankle moments were extremely large at the onset of independent walking (>> 100%). A rapid and significant decrease in variability was observed with increasing walking experience. The results of the exponential decay model are shown in Table 3. After 2 weeks of walking experience, interindividual variation in hip, knee, and ankle moments decreased to values of 20%–60%. Those percentages were similar in magnitude to the variation observed in movement kinematics.

Discussion

To our knowledge, this is the first study in which investigators have shown moment–angle plots in toddlers and used them to examine changes in mechanical control of movement

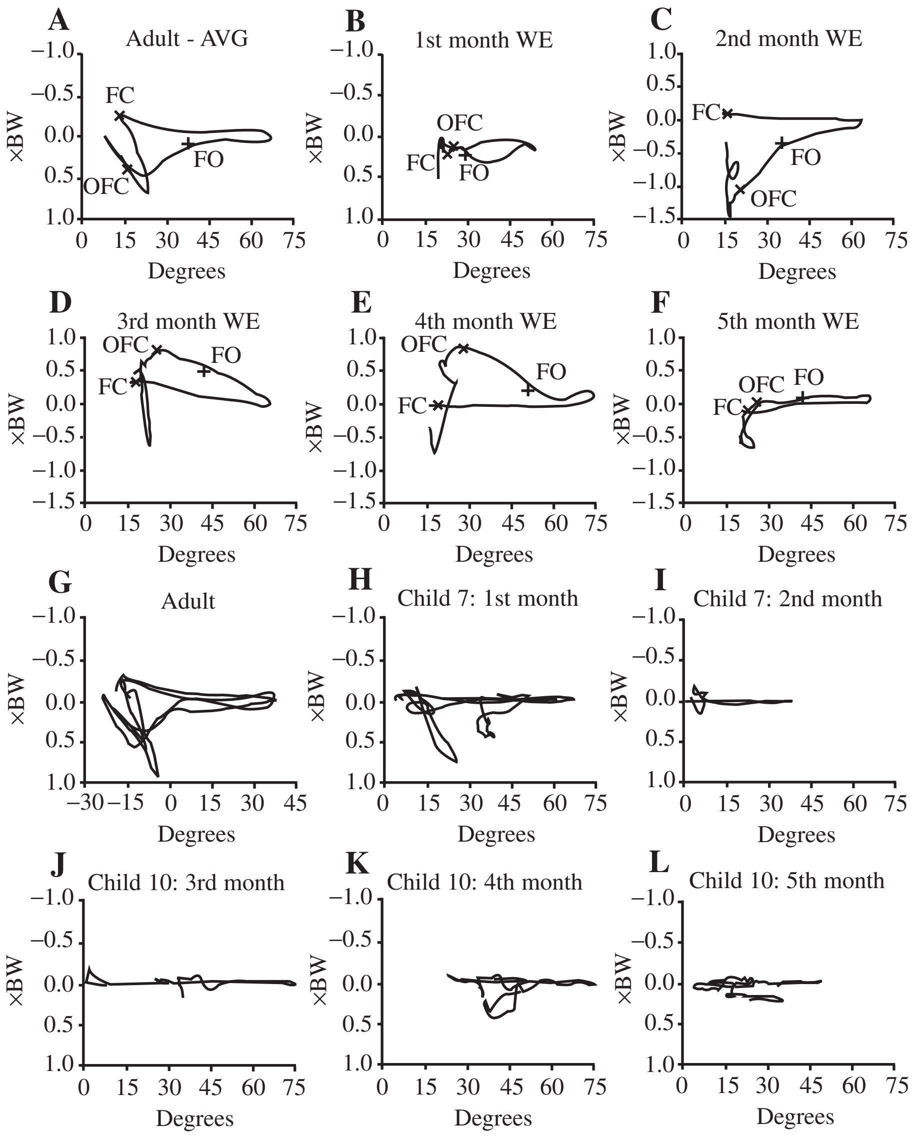

FIGURE 3. Moment–angle plots for the knee joint of adults compared with those of toddlers at the onset of independent walking (1st month) and after 2, 3, 4, and 5 months of walking experience (WE). (**A** to **F**) The session averages. On the average profiles, the instances of foot contact (FC), opposite foot contact (OFC), and foot off (FO) are indicated. (**G** to **L**) The different gait cycles from the same individual are plotted on top of each other so that one can see the repeatability of movement control. BW = body weight.

in that age group. We chose to perform a longitudinal study so that we could compare individual maturational trends. The frequency of returning to the gait laboratory was relatively high (in the beginning, every week), providing us with a detailed and large set of data. It appeared to be relatively difficult to convince parents of healthy children to participate in time-consuming research. Recording sessions frequently took 1.0 to 1.5 hr because we often had to make more than 20 recordings to obtain three to four good trials. Nevertheless, we were able to follow 10 children over a period of 5 months. The longitudinal nature of this study allowed us to use a smaller population size, and even with a small number of individuals, in-depth inspection of similarities or differences in gait maturation enhances the understanding of motor development.

Problems with cooperation of the children when markers were taped on the skin led us to use a highly elastic suit on which we could stick the markers (as shown in Figure 1). Cappello, Capozzo, Crocce, and Leardini (1998) discussed in detail the effect of different marker attachment methods (such as taping on the skin, using plates, or using highly elastic bands) on the validity of kinematic data. They showed that each method has its advantages and drawbacks.

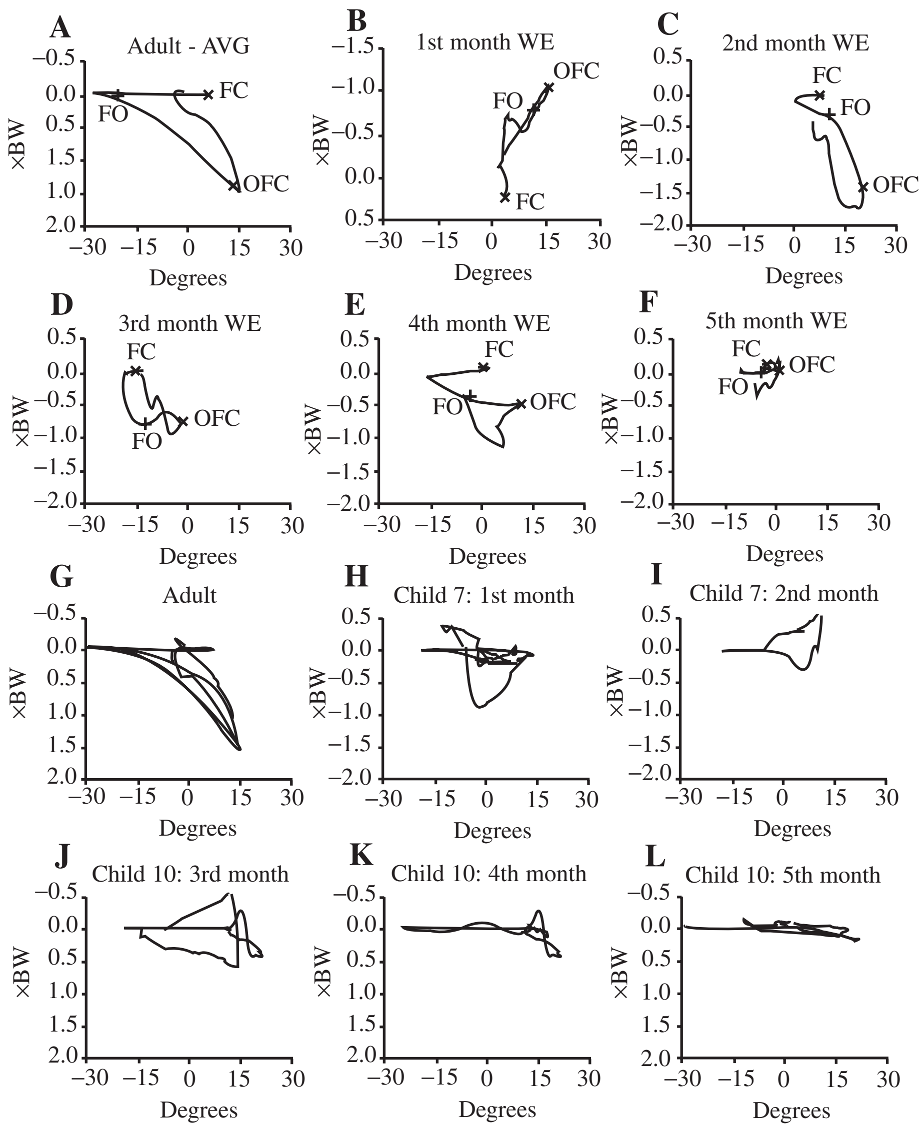

FIGURE 4. Moment–angle plots for the ankle joint of adults compared with those of toddlers at the onset of independent walking (1st month) and after 2, 3, 4, and 5 months of walking experience (WE). (**A** to **F**) The session averages. On the average profiles, the instances of foot contact (FC), opposite foot contact (OFC) and foot off (FO) are indicated. (**G** to **L**) The different gait cycles from the same individual plotted on top of each other so that one can see the repeatability of movement control. BW = body weight.

We chose to use the suit for several reasons. (a) It limited the children's ability to pluck off the markers. (b) It allowed us to obtain natural behavior because the children were less aware of the markers. (c) Capello and colleagues also argued that the use of wide elastic bands could limit skin artifacts. (d) Moreover, an elastic suit may help to limit those errors that are expected to be large in chubby toddlers.

Moment–Angle Plots

To investigate mechanical control of movement in the toddlers, we modeled the leg segments as oscillating pendulums fixed at the proximal joint. The moment–angle plots showed us that at the onset of independent walking, the muscles spanning the hip joint (one clockwise loop) actively controlled the movement of the thigh, whereas the knee musculature (one counterclockwise loop) passively controlled the movement of the shank. The moment–angle plot around the ankle joint was highly irregular at the onset of independent walking. Those findings suggest that in early walkers, movements of the leg segments are primarily hip driven. The large clockwise loop points toward a large amount of power generation at the hip joint. At the knee joint, power was primarily absorbed. The irregular moment–angle plots around the ankle suggested that the

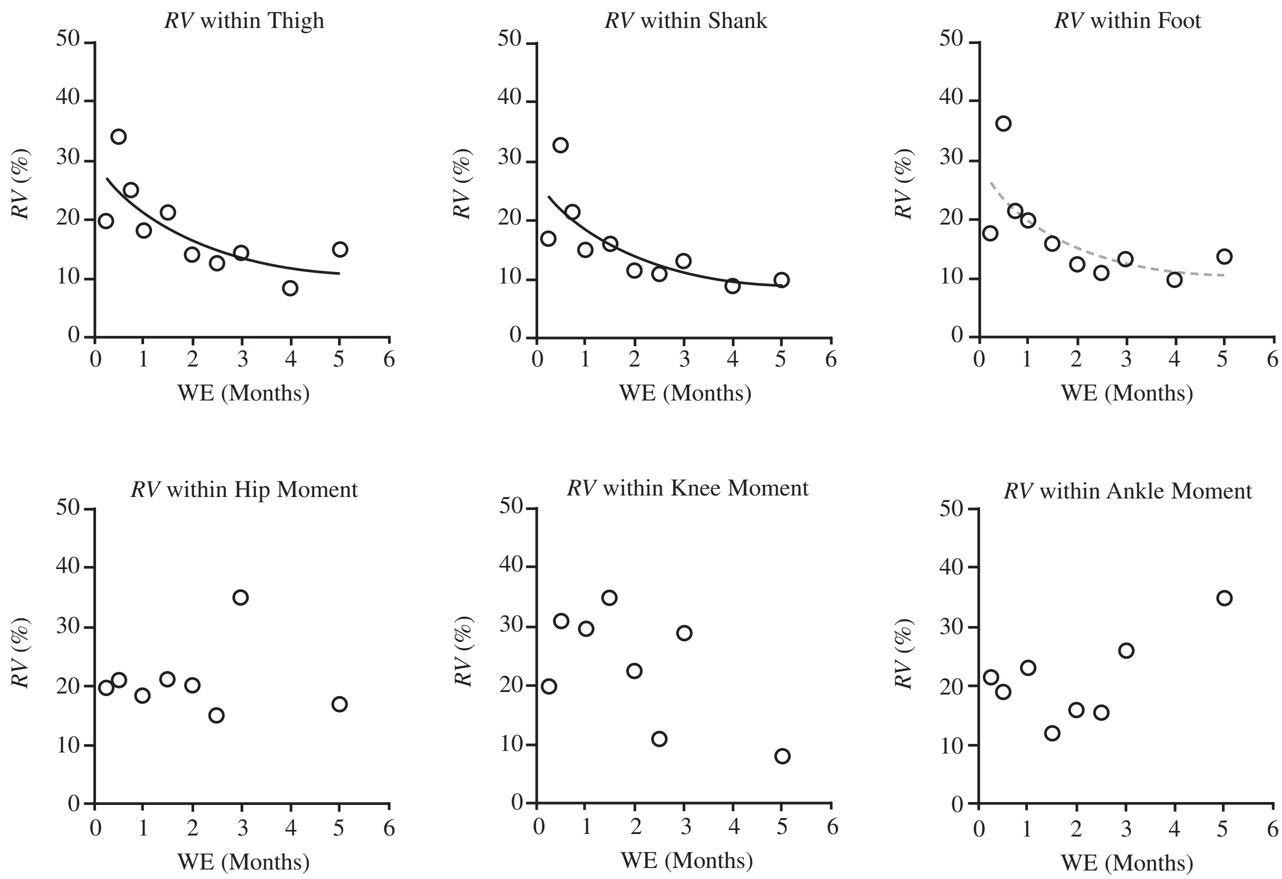

FIGURE 5. How intraindividual variability (*RV* within) in kinematic and kinetic time profiles changed with increasing walking experience (WE, expressed in months). The *RV* within of different individuals were averaged per session. The exponential decay model (details can be found in Table 2) was significant for *RV* within of the thigh and shank angles. Those curves are plotted here. The decrease in *RV* within of the foot angle showed borderline significance; therefore, the model is plotted in gray dashed lines.

muscles spanning the ankle joint were not very efficient for propulsive force generation. Those patterns of mechanical control of movement differ from what is observed in adults. In mature gait, propulsive forces are primarily generated in the ankle and, to a lesser extent, in the hip (Perry, 1992; Winter, 1991). Thelen and Fischer (1983) showed that biomechanical parameters such as muscle force could be important rate-limiters in motor development. In line with those findings, we suggest reasons why the toddlers powered gait primarily from the hip joint. One of many possible explanations is that the toddlers preferably powered gait from the hip joint because the hip muscles are stronger than the ankle musculature. During their previous experiences in kicking, sitting, and crawling, the children had already exercised the muscles spanning the hip joint, whereas before walking they had little exercise in using their ankle muscles.

In adults, at the hip, the knee, as well as at the ankle, shifts are observed between periods of active and passive mechanical control of movement. In their first months of independent walking, toddlers' mechanical control of walking is restricted to either active (at the hip) or passive (at the knee) control during the entire gait cycle. That restriction is reflected in the shape of the moment–angle plot (only one closed loop turning either counterclockwise or clockwise). It seems that toddlers have difficulties in shifting between active and passive control of movement and that they opt for the simplest solution. Similar phenomena in standing were reported by other researchers: Young toddlers just learning to stand fixed their joints in an extended position (Clark, 1995), relieving themselves from the daunting task of online compensation of minor imbalances. Developers of computational models of control, for example in robotics, also opt for reducing the number of independent joint variables to solve the problem of redundancy of the system (Sporns & Edelman, 1993).

With increasing walking experience, changes were observed in the shape of the moment–angle plots. After 4 months of walking experience, the average hip moment–angle plot resembled the mature form, with two loops, one turning clockwise (active control of hip extension at foot contact) and one turning counterclockwise (slowing down hip flexion in terminal swing). Around the knee joint also, changes were observed in mechanical control of move-

TABLE 3. Results of the Exponential Decay Model ($RV = y_0 + a{*}e^{-b{*}WE}$)

Variable	y_0	*a*	*b*	*F*	*df*	*p*	R^2	τ
				RV within (%)				
Thigh angle	9.60	20	0.54	4.96	2	.045	.59	1.85
Shank angle	7.70	19	0.57	4.58	2	.050	.57	1.75
Foot angle	9.94	19	0.68	3.72	2	.080	.52	1.47
Hip moment	21	—	—	—	—	—	—	—
Knee moment	24	—	—	—	—	—	—	—
Ankle moment	21	—	—	—	—	—	—	—
				RV between (%)				
Thigh angle	36	—	—	—	—	—	—	—
Shank angle	28	—	—	—	—	—	—	—
Foot angle	100	—	—	—	—	—	—	—
Hip moment	40	569	1.87	6.73	2	.050	.77	0.53
Knee moment	20	2,017	2.41	42.53	2	.002	.96	0.42
Ankle moment	60	4,460	7.13	214.53	2	< .001	.99	0.14

Note. Parameter estimates, R^2 values, results of the analysis of variance (*F* value, degrees of freedom [*df*], and *p* values), and the time constant (τ, in months of independent walking) of exponential decay are shown. If the model was not significant, then y_0 represents the average ratio of variability (*RV*). WE = walking experience. Dash (—) = no data were available.

ment after 3 months of independent walking. Following foot contact, a small counterclockwise loop emerged, reflecting the shock-absorbing knee flexion–extension wave. Changes in mechanical control of the ankle were less pronounced, however. They occurred only in a few individuals, and they reflected an increase in power generation for push-off.

Of interest is that the observed changes in mechanical control of movement occurred after 3–4 months. Clark and Phillips (1993) noted important changes in intralimb coordination after a similar time period. It seems that after a couple of months of walking experience, the different subsystems (e.g., muscle force, balance control, and movement control) determining the gait pattern have reached a critical level of maturity, and a jump in motor development is observed. Of course, the age at which that level of maturity is acquired will differ for all children, depending upon such things as previous experiences and biological factors.

Despite those clear maturational trends in mechanical control of movement, we often observed developmental reversals to more immature patterns of movement control. That became very obvious when we looked at the average moment–angle plots after 5 months of walking experience. Developmental reversals could be attributed to session-to-session differences in motivation of the children, which were very difficult to control. But other researchers studying movement coordination in young children (infants and toddlers) also often observed developmental reversals to immature patterns (Clark & Phillips, 1993; Jensen, Schneider, Ulrich, Zernicke, & Thelen, 1994; Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1995). Those findings show clearly that development is a nonlinear process that leads to continuous improvement, especially when one considers shorter time intervals. That nonlinear view on development is reflected in the description of development as an *epigenetic landscape* (Thelen, 1995). Periods of learning are marked by low dynamic stability that also affects previously learned skills.

Variation in Mechanical Control of Movement

Intraindividual variation in segment angles and joint moments were moderate to large at the onset of independent walking. A high amount of variation is expected when a new skill is acquired (Clark, Whitall, & Phillips, 1988; Thelen, 1995). It results from the redundancy of the motor systems, and it is necessary for exploration of many possible solutions that satisfy the task constraints. The exponential decay model showed a significant decrease in RV_{wi}s for the thigh, shank, and foot angles with developmental time. That finding suggests that the kinematics of walking (the endproduct) is already relatively stable but that the system is still looking for the most efficient way of mechanical control.

Variations between individuals in hip, knee, and ankle moment profiles were extremely large at the onset of independent walking. That observation shows that at the onset of walking, each child has its own strategy for walking. The resulting gait pattern (reflected in the thigh, shank, and foot angles) is less variable because constraints in the task of walking and in the environment limit the possibilities of movement variation (Winter, 1991). A rapid decrease was seen in *RV*s for the hip, knee, and ankle moment toward the range observed for joint kinematics. Thus, the children rapidly evolved toward more similar patterns of mechanical control (although dynamic instability remained large).

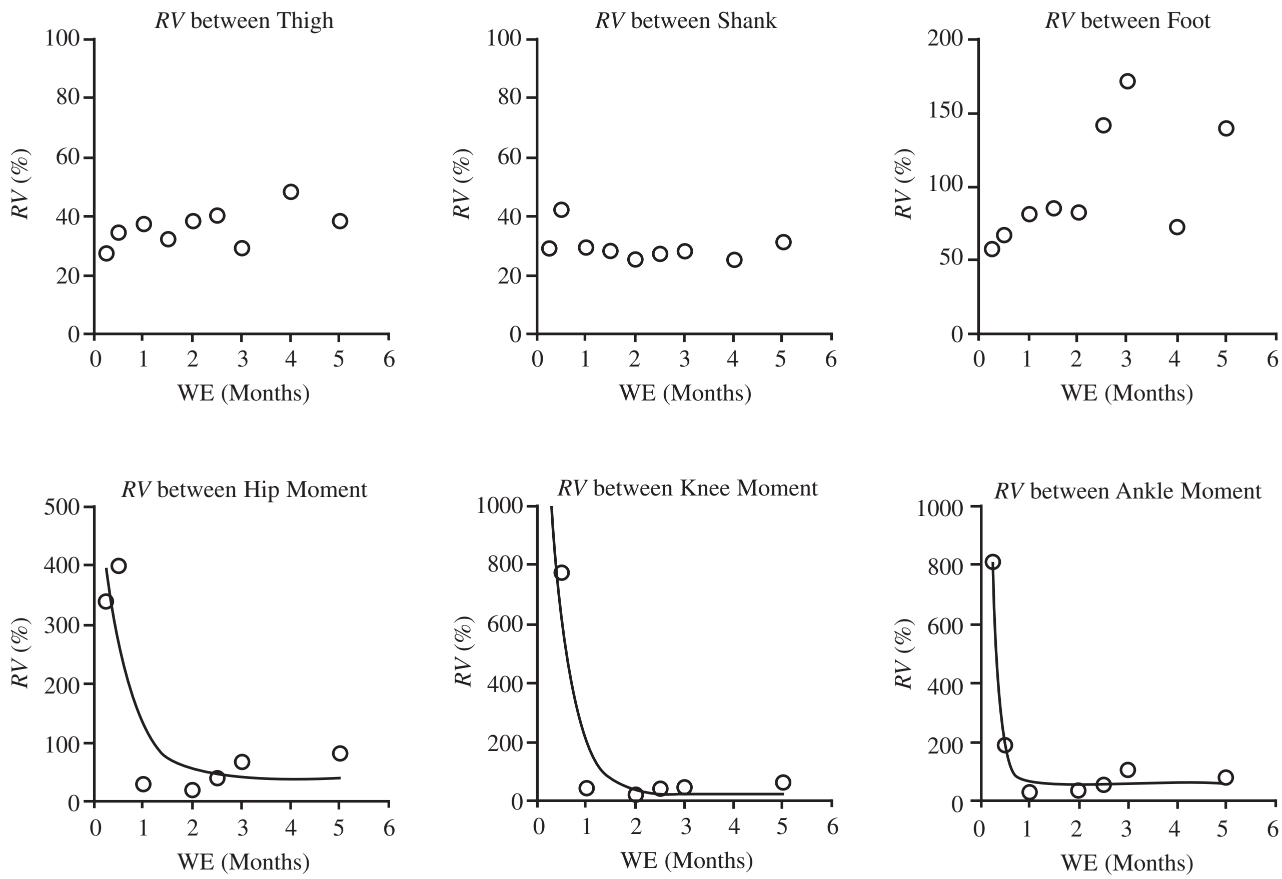

FIGURE 6. How interindividual variability (*RV* between) in kinematic and kinetic time profiles changed with increasing walking experience (WE, expressed in months). The exponential decay model (details can be found in Table 2) was significant for *RV* between of the hip, knee, and ankle moments. Those curves are plotted.

Conclusion

In this study, we were able to follow 10 children intensively from the onset of independent walking until they gained 5 months of walking experience. One can use oscillating pendulums fixed at the proximal joint to model evidence for the mechanical control strategies of walking in toddlers.

Important observations were that at the onset of independent walking, gait is primarily hip driven. Furthermore, young children have difficulties in uncoupling mechanical control of movement at a joint. Changes in the mechanical control strategies of walking were observed after 3–4 months of walking experience. Researchers have noted improvements in interlimb and intralimb coordination after a similar time period. Therefore, changes in mechanical control of movement possibly lie at the basis of improvements in movement coordination.

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Biographical Notes

Ann Hallemans is a postdoctoral researcher at the University of Antwerp with main interests in the process of motor development and motor control. She also teaches biomechanics at the University College of Antwerp). Lin Dhanis is a physiotherapist who collaborated in this research project as an undergraduate student. In his research, Peter Aerts's focuses on the biomechanics of the musculoskeletal system and the coupling between morphology and function in animals and humans. He teaches biomechanics, functional morphology, embryology, and ecomorphology. Dirk De Clercq teaches biomechanics at the University of Ghent. His research interests are biomechanics and motor control.

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The **Journal of Motor Behavior**, a multidisciplinary journal of movement neuroscience, publishes articles that contribute to a basic understanding of motor control. Articles from different disciplinary perspectives and levels of analysis are encouraged, including neurophysiological, biomechanical, electrophysiological, psychological, mathematical and physical, and clinical approaches. Applied studies are acceptable only to the extent that they provide a significant contribution to a basic issue in motor control. Of special interest to the Journal are those articles that attempt to bridge insights from different disciplinary perspectives to infer processes underlying motor control. Those approaches may embrace postural, locomotive, and manipulative aspects of motor functions, as well as coordination of speech articulators and eye movements. Articles dealing with analytical techniques and mathematical modeling are welcome.

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Biographies of the Editors of the *Journal of Motor Behavior*

RICHARD G. CARSON spent his youth in Northern Ireland. He received his undergraduate degree in psychology at the University of Bristol. Thereafter he did graduate research at Simon Fraser University in Vancouver, Canada. He held a number of research fellowships at the University of Queensland in Brisbane, Australia, where he was appointed to a research professorship in 2002. At the beginning of 2006, he returned to Ireland to serve as professor at Queen's University Belfast. His research focuses on neural plasticity—that is, the capacity of the central nervous system to adapt in a manner that generates new functional capabilities or restores functional capabilities that have been lost, for example, because of brain injury or aging. He has served as an Executive Editor of the *Journal of Motor Behavior* since 2005.

ROBERT L. SAINBURG did his undergraduate work at New York University, where he received a baccalaureate in occupational therapy and subsequently practiced in clinical neurorehabilitation. He received his master's degree in physiology and neurobiology and his doctorate in neuroscience from Rutgers University. He then did postdoctoral research under the mentorship of Claude Ghez in the Department of Neurobiology at Columbia University in New York. He is now an associate professor of kinesiology and neurology at The Pennsylvania State University. In his research Dr. Sainburg integrates biomechanical with neurobiological principles to elucidate the neural processes underlying the planning and execution of multijoint movements and bilateral coordination and to describe the mechanisms underlying coordination deficits. His research program is ultimately directed toward effecting improvements in clinical rehabilitation. He has served as Executive Editor of the *Journal of Motor Behavior* since 2007.

DAGMAR STERNAD is a full professor at the Department of Kinesiology and the Integrative Bioscience Program at the Pennsylvania State University. Following her undergraduate work at the Technical University of Munich, Germany, she received her master's and doctoral degrees in experimental psychology working with Michael Turvey at the University of Connecticut. After graduating in 1995 she began working as assistant professor at The Pennsylvania State University where she has since established a productive research group. She has been Executive Editor of the *Journal of Motor Behavior* since 2005. Her interdisciplinary research program has several prongs: (a) the development of a unified framework for discrete and rhythmic movements with nonlinear dynamics as the theoretical framework, (b) a task-dynamic approach to a rhythmic movements with a special emphasis of the role of dynamical stability, (c) variability decomposition to understand learning and development, and (d) the detection of gait. The methods comprise an empirical component with behavioral experiments on human subjects, theoretical work that develops mathematical models for movement generation on the basis of coupled dynamical systems, and brain imaging studies (fMRI) to examine the cerebral activity. More recently, she has applied her experimental paradigms to neurological disorders such as Parkinson's disease and split-brain patients.

DANIEL M. CORCOS Rapid Communications Editor of the *Journal of Motor Behavior,* obtained his doctorate in motor control from the University of Oregon in 1982 after obtaining his master's degree in psychology in l980. Dr. Corcos was an assistant professor at the University of Illinois at Chicago from l987–l993 and was promoted to the rank of associate professor with tenure in l993 and to full professor in l997. He served as Executive Editor of the *Journal of Motor Behavior* from 1997 to 2004. In addition to his work as the journal's Rapid Communications Editor, he is on the editorial board for the *Journal of Neuroengineering and Rehabilitation*. Dr. Corcos currently is involved in four lines of research. The first is related to the motor deficits associated with Parkinson's disease and how different neurosurgical interventions can facilitate the control of movement in Parkinson's disease. The second relates to the role of the basal ganglia in the control of a wide variety of movement tasks. The third relates to the central control of reflexes during voluntary movement. Finally, he is interested in the role of exercise in reducing the negative impact of progressive neurological disorders.