Forms of Early Walking

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Children in the first weeks of independent locomotion display a wide variety of walking forms. The walking forms differ in mechanical strategy and concern with balance. Three extreme walking forms are presented: the Twister, who uses trunk twist, the Faller, who uses gravity, and the Stepper, who remains balanced as much as possible. Each walking form is presented as a “d-space”, a mathematical format combining continuous and discrete aspects, developed to express the sequence and pattern of a movement without the inappropriate precision of a physical trajectory. The three d-spaces represent analyses of three extreme modes of early walking. They are used to generate the variety of early walking forms and to predict mixtures of mechanical strategies as children mature and converge to more similar walking forms over the first few months of independent locomotion.

1. Introduction

A ball can be thrown overhand or underhand. Each of these two throwing strategies is governed by Newtonian mechanics and can be described with mechanical completeness in terms of forces, levers, and so on. Furthermore, overhand and underhand throwing can be understood as two options provided by the human musculoskeletal structure and human upright stance in a gravitational field. Other imaginable throws are not mechanically effective options, for example an intermediate throw in which the ball is propelled straight forward from the shoulder. So (in the sagittal plane) mechanics gives us the choice between an overhand and an underhand throwing strategy.

This paper looks at the mechanical strategies children use during the first few weeks of independent locomotion. To express such movements in terms of differential equations—which is possible because they are governed by classical mechanics—would be too complicated to yield insights and would obscure the fact that the movements are composed of bundles of alternative trajectories. Instead, we will use a discrete formalism called a “d-space”, which represents, as its elements, the parameter regions reached by bundles of mechanical trajectories. (Section 2 introduces d-spaces more thoroughly.) Such a discrete formalism offers a means for evaluating the components of walking that are relevant to the nervous system, the way the nervous system organizes the control of complex movements, the nervous system’s repertoire of complex movements, and modes of combining or modifying complex movements that the nervous system may use. To illustrate mechanical, experimental and clinical approaches to mechanical strategies, we will review a simpler movement: fast postural adjustments.

Fast postural adjustments are movements for returning to upright stance after a sudden perturbation. Two of the major mechanical strategies are the ankle and the hip movements (Nashner & McCollum, 1985). Although Newtonian mechanics applies equally to the two movements, each exploits a different aspect of the mechanical options. In the ankle movement, the
muscles are coordinated to deliver a torque at the ankle, returning the ankle angle to approximately 90 degrees. In the hip movement, an abrupt hip torque results in shear forces on the floor and the return of the center of mass to above the feet. Thus, while torques and shear forces are at play in both movements, the two strategies can be distinguished by key aspects of their interaction with the floor: the ankle strategy exploits ankle torque, whereas the hip strategy exploits horizontal shear forces.

Experimentalists use various measures to distinguish the two strategies. The characteristic muscle activation patterns are different (Horak & Nashner, 1986). They are also kinematically different, distinguished by the almost straight body of the ankle movement versus the large hip excursion of the ankle strategy (Shupert et al., 1992). In addition, different head movements and neck muscle activity patterns are associated with each postural movement (Shupert et al., 1988). Experimentalists also measure the torque and shear forces exerted on the support surface (Horak & Nashner, 1986).

Clinically, the use of the different postural strategies is often readily apparent. Mechanical understanding of the two postural adjustment strategies has led to changes in therapy (Shumway-Cook & Horak, 1990). Also, the use of a particular strategy can be helpful in diagnosis as use of only the ankle strategy is associated with lack of vestibular gain (Horak et al., 1990), whereas use of only the hip strategy is associated with other disorders, such as positional nystagmus of various types (Shupert et al., 1992). In addition, different head movements and neck muscle activity patterns are associated with each postural movement (Shupert et al., 1988). Experimentalists also measure the torque and shear forces exerted on the support surface.

The purpose of this paper is to show how d-spaces can be used to analyze different forms of early walking. Three forms using different mechanical strategies are presented as examples of the diversity of early walking and to show how the different mechanical strategies are expressed in d-spaces. Descriptions of children that we have observed, who appeared to be using the three different mechanical strategies, are included to clarify and motivate the theoretical development.

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2. Theoretical Methods

This paper presents a framework for understanding and describing early walking forms. The mathematical formalism—d-spaces—used to describe the early walking forms is introduced in this section.

A d-space is a set of regions with relations of inclusion and contiguity (McCollum, 1994a, b). The regions are continuous; the relations between them introduce the discrete aspect of movement. (The “d” in “d-space” is for “discrete”.) The set of regions in a d-space specifies the variables parameterizing the regions and the tolerances for them, for example, for position of foot placement, for maximal hip angle, or for trunk angular momentum at heelstrike. Only the regions relevant to the movement are specified in the d-space; if a particular variable is irrelevant or is monitored by something already specified, then it is omitted.

Inclusion of a region in a functionally relevant region is expressed by the inclusion relation. This is an inherently discrete relation, because the movement as a whole is inappropriately controlled if certain requirements are not met. For example, in placing a foot on the next higher step while walking up steps, the foot can be in a range of locations on the step, but the control is inappropriate if there is a significant probability that the foot will miss the step altogether.

Contiguity allows expression of the order in which regions must be reached. For example, the swing foot must be put down, in a walk, before the stance foot is lifted. In this paper, the sequence of movements has been connected by directed contiguity, indicated by dashed arrows, because of the sequential nature of the walking movement. It seems a natural specialization, following the usage of directed edges in graph theory. Also, directed contiguity expresses the physical possibility for the body to move from one region to the next contiguous one. Contiguity is an algebraic expression of a set-valued map (Aubin & Cellina, 1984).

3. The Variety of Early Walking Forms

This section presents a rationale for understanding the variety of early walking forms as a result of the sequential integration of mechanical strategies in different orders and degrees in different children. First, the variety and the use of different mechanical strategies (even though the same array of physical laws applies) will be illustrated by describing three early walking forms, those of the Twister, Faller and Stepper (Fig. 1). For additional vividness, the reader is encouraged to try each form.

The Twister’s walk could be considered a torque or angular momentum strategy because of the Twister’s prominent use of vertical torque and angular momentum, or twist, even though gravity and leg muscle forces are certainly active. Twist torque (vertical torque) is produced by the trunk muscles acting against the firm base of the legs, so that a reaction torque (vertical) is exerted on the support surface. The Twister appears to wind up the trunk like a spring (Fig. 1Ai), then lets fly, bringing the swing leg around front using the torque and angular momentum of the trunk (Fig. 1Aii). The feet stay about the same distance from each other, so that the motion of the legs is like the motion of a drawing compass. For the next step, the trunk is wound up in the other direction (Fig. 1Aiii). Then the other leg becomes the swing leg, propelled around to the front by the twist power of the trunk in the other direction (Fig. 1Aiv). Balance is easily maintained, because the feet are always wide apart and each double-stance phase is solid, with no forward momentum. The Twister can easily stop between steps. This is a symmetrical Twister; Twisters can be asymmetrical, but an asymmetrical Twister will tend to go around in circles if one leg does not mix its twist with another mechanical strategy. [At least one apparent Twister was found among Sveistrup and Woollacott’s subjects, (1995).]

The Faller’s walk is based on the exchange of gravitational potential energy for kinetic energy in a fall, followed by the generation of potential energy by stretching tall again. The Faller’s walking form could be considered to use a gravity strategy, even though leg muscles and vertical torque are certainly active. The Faller stands high on tiptoe for an instant, not really balanced, but falling forward only slowly at first (Fig. 1Bi). The next three illustrated positions pass quickly. The fall speeds up and the Faller puts the swing foot forward to break the fall, and to turn the downward momentum into forward momentum (Fig. 1Bii). A quick step, low to the ground (Fig. 1Biii), brings the Faller back to the original stance foot (Fig. 1Biv). The kinetic energy gained by falling is slowed somewhat by rising again onto one tiptoe (Fig. 1Bv). This is an asymmetric Faller; some Fallers are more symmetric, seeming to launch across the floor and leave their feet hurrying to catch up. For any Faller, balance is precarious at each phase of the step cycle, so that the Faller cannot stop without something to bump into (such as a wall or friendly adult). [At least apparent one Faller was found among Sveistrup and Woollacott’s subjects (1995).]

The Stepper’s mechanical strategy could be described as a conservation or balance strategy, because the Stepper makes only very small excursions
Three forms of early walking, exemplifying three different mechanical strategies. (A) Twister; (B) Faller; (C) Stepper. Further details are given in the text.

From a stable, balanced double stance. The Stepper, like the Twister, is solidly balanced at each double-stance phase and stands erect (Fig. 1Ci). The Stepper takes small steps, lifting one foot by bending the knee (Fig. 1Cii). The foot is quickly replaced, without much falling or twisting movement of the body (Fig. 1Ciii). Similarly, the other foot is lifted for a short step (Fig. 1Civ) and quickly, put down again (Fig. 1Cv). Different Steppers lift the knee by different amounts; a Stepper walk with a high knee-lift looks like a march.

Each walking form is strikingly different. The Faller does little besides fall, whereas the Twister and the Stepper fall very little. The Twister’s body twists are very large compared to those of the Faller and the Stepper. The Stepper uses almost pure leg muscle power; although the Twister and the Faller use significant amounts of leg muscle power, the Twister augments it with lots of trunk muscle power and the Faller augments it with a gravitational strategy. In addition, there are variations like the side-to-side Faller, who makes very little progress forward while making large swings from side to side; this walk is unusual for a Faller, because double stance is fairly stable. The three examples, Twister, Faller and
STEPPER, are not a classification of early walking forms, but an illustration of a widely varied phenomenon.

VARIETY

What features of early walking could lead to all this variety? The framework we propose assumes that children’s walking forms are limited by the mechanical strategies they have integrated. The limitations imposed on children’s walking forms by other factors are interdependent with those imposed by integration of mechanical strategies; strategies are only adopted if they are mechanically and physiologically functional. A number of assumptions about the integration of mechanical strategies in the first months of independent locomotion help to explain the variety of early walking forms. They are stated below so that they will not join the great mass of unconscious assumptions.

Simplicity. Children walk with a small repertoire of mechanical strategies.

In contrast, adults intertwine a greater number of mechanical strategies. For example, the physics of the compound pendulum tends to be integrated late (Brenière et al., 1989; McCollum & Leen, 1989). Adults combine the compound pendulum and its dependence on gravitation with the mechanics of twist, etc., into an individualized and mechanically complex movement. It may be that children walk as soon as they have a repertoire of mechanical strategies that allows them to walk. Gracefulness or completeness is not required. The assumption of mechanical simplicity motivates the analysis of mechanically extreme early walking forms and their convergence over time.

Consistency. Once a child walks, further mastery of mechanics augments and modifies the existing walk, rather than being used as an alternative.

This assumption both motivates the convergence of early walking forms over time and helps to explain our observation that children tended to maintain their walking form. In contrast, Vansant (1988) found that children rising from a stand by lying down use different movement forms in successive trials, whereas adults are more consistent.

Separable components. The repertoire of walking movements that each child displays can be separated into components with recognizable physical functions.

An adult’s walk blends movement components into a graceful whole, so that movements with different purposes may overlap, the variables parameterizing a movement may be a subtle combination of different factors, and different forms of movement efficiency are combined. For these reasons, it is difficult to parse an adult’s walk into functional components just by watching. Adults have the benefit not only of many mechanical strategies but also of practice, so that the muscles work optimally to produce the desired movement (Schneider et al., 1989). Also, an adult’s walk may contain stylistic frills, not entirely necessary to locomotion. Similarly, a child learning to speak may simply mimic an adult, with no intention to communicate. The assumption of separable components follows from the assumption that children tend to use few mechanical strategies and motivates the analysis of mechanically extreme forms of early walking.

4. Early Walking Forms

This section specifies three mechanically extreme early walking forms in detail. Each form maintains certain invariants that are specified in the d-space. If an invariant is maintained throughout the walk, it is shown at the top, formalized as a region of a movement space that includes all of the regions passed through as the child moves through the various phases of locomotion. The invariants will be presented first, then the phases of locomotion for each early walking form. The d-space diagrams (Figs 2–4) are central to the presentation; much of the text functions as explanations of the figures.

INvariants

Each form of early walking can be specified as a complicated region of a many-dimensional movement space; each such region is a subset of the region representing all forms of walking. Each d-space (Figs 2–4) has the region of all walks at the top, specified by “Go forward without falling, with weight alternating between the two feet”. “Forward” simply means the direction the walker is going, so that “Go forward” means “Go in one direction”, rather than back and forth, as in rocking from one foot to the other. “Without falling”, in this context, means “without falling so far that further walking is impossible”; when children sit down abruptly or fall forward so that they catch themselves with their hands, they are no longer walking.

Another large region is the region of all walks with a wide-based gait. Following convention, inclusion is expressed by connection with a line, so that the included region is lower on the page. The region of all walks with a wide-based gait is shown included in the region of all walks. Inclusion in the d-spaces in this paper always means inclusion of a region within a region (such as the Great Plains within North America), rather than the inclusion of an item within a set of discrete elements (such as a spoon within a set of silverware). For this reason, the word “region” is always used for a subset of a continuous space, and the
Go forward without falling, with weight alternating between the two feet.

Wide-based gait (right-left wide, with respect to body)

Fig. 2. A d-space representing a Twist walk. Some of the graphical notation, especially the squares with missing corners, are explained in Fig. 5. The walk follows a sequence of specific regions connected by a cycle of dashed arrows. For the performance of each swing phase (the flinging around and forward of the swing foot), two options are shown as regions included in the particular swing phase regions (square graphs with shaded circle regions). One option is muscle power, represented by a region of trajectories in shoulder and base angle space (Fig. 5). The other option—building trunk angular momentum and then flinging—is represented by a sequence of two regions of trajectories. Further details are given in the text.

The word “set” is used only for discrete sets. The top two invariants, the region of all walks and the region of all walks with a wide-based gait, are the same for each of the example d-spaces (Figs 2–4).

Within the region of wide-based gaits, the three examples are distinguished by the amount of vertical, lateral and right-left movement. Here, “lateral” means perpendicular both to vertical and to the direction of motion. It is different, especially in the Twist walk, from “right-left”, which will be used to mean the body’s own right and left. Limitations of movement are specified in each d-space (Figs 2–4) just below wide-based gait, because they specify types of movement within the region of wide-based gaits.

Whereas the Faller moves vertically against gravity to gain potential energy, the Twister avoids all vertical movement except the small amount required to move the foot (Fig. 2) and the Stepper avoids vertical trunk movements (Fig. 3). The Faller and the Stepper avoid lateral movements of the trunk and of the feet (Figs 3–4). The Stepper is always balanced in the sagittal direction, as indicated by a sagittal stability cone icon (Fig. 4). The Twister’s movements have separate limitations for the right-left and lateral directions. The Twister maintains the legs and hips fairly consistently within an upright right-left plane. Also, the feet and trunk make no right-left linear motions, although the trunk twists about its vertical axis. Because of these limitations of motion, the body is always stable in the sagittal direction, where “sagittal” refers to body front-back (as opposed to “forward”, meaning in the direction of motion). An icon representing sagittal stability is included in the d-space diagram as a visual reminder (Fig. 2). Even though the twisting motion involves lateral movement of everything except the vertical axis of the body, there
is no overall lateral motion because the clockwise and counterclockwise twists are equal in amplitude, as specified as a graph showing equal-amplitude twist angles for the right and left swing phases (s(R) and s(L); see Fig. 5A). (Actually, early walkers tend to veer to one side, so this requirement could be broadened to relate the right-left difference in leg twist angle to the radius of the veer.) These limitations of motion are the last invariants applying to the whole form of the movement. Formally, the elements of each d-space specifying limitations of motion are regions of movement that accomplish wide-based walks obeying certain limitations of motion.

**PHASES**

Each walk can be divided into phases, which may differ between forms. In each d-space (Figs 2–4), the region of movements that accomplish wide-based walks obeying certain limitations of motion includes a sequence of movement regions that are the phases making up the walk. Each d-space has a level of phases connected by dashed arrows, showing the cyclic nature of walking. Each d-space specifies a stance-swing-stance-swing sequence.

**TWISTER PHASES**

To the left of the Twister d-space is the specification “right-left stable”, accompanied by an icon (Fig. 2). During double stance phase, the Twister is not only stable in the sagittal direction, but also in the right-left direction. The Twister is not right-left stable during the leg-twist or swing phase, so the specification of right-left stability is not included on the right.

The regions immediately included in the right-left stable region of the Twister d-space specify the trunk twist that prepares the power for swinging the foot around. The regions (shaded) are denoted in squares with missing corners, which are graphs whose variables are explained in Fig. 5A–C. Head-and-feet icons are included for ease of reading the d-space diagram. The clockwise (looking from above) trunk twist performed with the left foot forward, in preparation to swing the right foot around and forward, is specified by the leftmost sequence of squares with missing corners (Fig. 2). They are connected by a dashed line that denotes contiguity—the child moves from one region to the other. The arrow shows that the child moves in only one direction during this phase of the movement. Just past halfway across the diagram, at the same level (found by following the dashed arrows), is the other pair of regions in squares with missing corners; the
second pair represents the counterclockwise trunk twist performed with the right foot forward, in preparation to swing the left foot around and forward.

For the swing phase of the Twister walk, there is a requirement that the foot be off the ground long enough to finish the twist, rather than falling back to the ground first. This requirement is specified both in words and as a graph in the d-space diagram, to the right of the double stance phase specification of right-left stability (Fig. 2, square graph of duration×width of base, with broad black diagonal band). Included in this region are the two specifications of the individual swing phase angles and durations (Fig. 2, smaller squares containing round regions). Although the angles are required to be approximately equal in amplitude (but opposite in sign), the durations may be quite different, so the angular velocities of each swing phase’s twist may differ.

The next level down in the Twister d-space is included to illustrate the way a choice of implementation strategies may be represented in a d-space. The swing leg may be rotated about the stance leg by pure muscle power, as denoted by a trajectory, marked “muscle power”, in the square with missing corners that represents a graph of shoulder angle versus leg and hip angle. Another option is to build trunk angular momentum, then transfer that angular momentum to the leg. The second option, using angular momentum, is represented by a sequence of labelled graphs. The sequence representing the momentum option is connected by a dashed arrow. Note that the muscle power option is not connected to the momentum by dashed lines or arrows; the two options are choices, rather than a sequence, because each is mechanically viable.

Similarly, all three early walking forms could be included in one conglomerate d-space, as choices under a wide-based gait. However, the children we observed did not switch from one form to another, but consistently used only one form. So such a conglomerate d-space would not represent the repertoire of one child, but of a conglomerate of children.

Fig. 4. A d-space representing a Stepping walk. Further details are given in the text.
FALLER PHASES

The Faller places the body in the best position to use a gravity strategy: as high as possible, so as to have as much gravitational potential energy as possible. Even the arms tend to be raised higher in the stance phase on the rising foot. (Arm positions are omitted from the d-space diagrams, partly to reduce complications and partly because arm positions do not seem to be essential to the walking forms.) During the Falling walk, the Faller does not remain in one position with the feet flat on the floor long enough to obviously be using standing balance (although all Fallers that were observed were also known to be proficient standers). However, the high beginning position is also extremely erect. For that reason, it is shown on the left of the Faller d-space (Fig. 3) as being included in the left-foot standing stability cone, both by a stick figure and by a round graph notation explained in Fig. 6. It is not clear that the Faller is ever really balanced either sagittally or laterally. However, the lateral balance/imbalance does not change, whereas there is a dramatic variation in sagittal stability.
Fig. 6. Diagrams and graph explaining round graph notation used in the Faller and Stepper d-spaces (Figs 3 and 4). (A) Definition of leg angles to vertical in the sagittal plane. Heavy lines are stick figure human legs. Dashed lines show the direction of gravitational vertical. Light lines join the hip to the ankles; the leg angles are the angles between these light lines and the vertical, as indicated by arcs. (B) Two-dimensional leg angle space, with one axis for each leg. The axes are used to develop a schematic diagram to display relations between regions of body position space. A more accurate display may be required in some cases. The center circle includes erect stance at the origin and small variations around erect stance. The second circle contains small deviations from the vertical, still within the mechanical stability cone (McCollum & Leen, 1989), plus foot separations involving small leg angle displacements. Between the second and outer circles, deviation from the vertical with the feet together is mechanically unbalanced, but some other positions are balanced, depending on the supporting foot or feet. (C) Narrow region around erect stance. The foot or feet that are supporting the body are indicated in black in each diagram. This is a notational short cut, abbreviating the distance to the floor as contact or no contact. Even though it is possible to have a foot in contact with the floor and not available to bear weight (for example, because of pain or for mechanical reasons), for the purposes of this paper it will be assumed that a shaded foot is in contact with the floor and available to bear weight. The position of erect stance is balanced for each support configuration, so each diagram is underlined, indicating a balanced position.

In the round graph notation, the left footprint is blackened to show that the left foot is on the floor and bearing weight (Fig. 3). (It is not meant to specify that the foot is flat on the floor.) The stripe across the diagram is the region of all sagittal foot positions in which the body can be balanced on the left foot. Included in that region is the small central region shown just below: exactly vertical, with both feet over the point of support. The round graph notation does not specify height off the floor, so that is shown as a separate line just below: the region is at the end, as high as the child can stand. The line is enclosed in a box of ×’s instead of creating a three-dimensional graph, which would be difficult to read. Standard mathematical notation for specifying a product space that includes dimensions from two or more spaces is to put an × between the two spaces. By enclosing multiple graphs in a box of ×’s, we can denote one region of many dimensions.

Aside from the high position, the Faller did not seem to control height, although the height fell. Rather, in each swing phase, the foot was placed simply to avoid falling entirely. In the Faller d-space, the two other phases (after the high position) can be controlled in various ways with the same result. One possibility is that foot placement is controlled by timing the interval since the body passed the vertical position over the stance foot and placing the swing foot at an appropriate distance forward. This method of control is depicted in the Faller d-space (Fig. 3). Another possibility is that foot placement is controlled by the momentum reached and the sway angle (Fig. 7).
Alternative control variables for placing the swing foot during the Falling walk. (A) The variables shown as part of the Faller d-space. The first time a swing foot breaks a fall, the duration of the swing is fairly long and the extension of the swing foot is correspondingly far (Fig. 1Bii), as indicated by the shaded region in the first graph. However, the Faller is now closer to the ground, so the second time a swing foot breaks a fall, the step is shorter (Fig. 1Biii): the duration is much shorter and so is the extension of the swing foot, as indicated by the second shaded region. Further details are given in the text. (B) An alternative set of control variables. Rather than controlling the placement of the foot according to the extent and duration of the step, the child may judge when to place the swing foot by the speed of the fall, because gravity speeds up the fall with time. When forward momentum reaches a certain range, the swing foot is placed within a corresponding range of forward angles. The first time a swing foot breaks a fall, the fall is allowed to go on until it is fairly fast, and the swing foot is placed directly under the child (Fig. 1Bii). The second time a swing foot breaks a fall, the fall is stopped before it has become so fast, but the swing foot is still placed directly underneath the child.

Individual children may use the same movement form, but control and sense it according to different variables.

In the Falling walk, there is no need to equalize step length. Another striking feature is that although stance phase and swing phase are clearly present, they seem secondary to the fall and catch cycle. They do not clearly appear in the d-space. The blurring of stance and swing phases may happen because the child is never static and cannot stop unaided during the walk.

**STEPPER PHASES**

In strong contrast to the Faller, the Stepper’s primary consideration seems to be maintaining balance. Double stance is a major phase, both definite and long. Double stance is shown on the left of the d-space (Fig. 4) both by a stick figure and by a round area, with both feet in black, in the round graph notation (Fig. 6). Included in the main, large, round double stance region are four particular stance phases, two between each stepping phase. Double stance is used to shift the weight forward onto the next stance foot, as shown by the stick figures and the round graph notation. Perhaps the strong separation into double stance versus stepping phases arises from the concern to maintain balance.

In the stepping phase, wide-based gait forces the Stepper to include a falling phase in the right-left direction. (The Stepper’s steps are so short that the lateral and right-left planes are almost the same, but one foot is usually in front of the other.) The width of the base limits the duration of the stepping phase, because gravitational acceleration is strongest when the center of mass is farthest from the stance leg. The relationship between width of base and duration of step in the stepping phase is indicated in the d-space by a square graph to the right of the double stance phase round graph (Fig. 4). Included in the general relationship for the stepping phase is a box of ×’s for each (right and left) stepping phase. Within each box of ×’s is a square graph showing the particular region of forward movement and step duration for that step. With the square graph in each box of ×’s is also the round graph notation showing that the Stepper is always balanced on the stance foot in the sagittal plane.

**SUMMARY OF D-SPACES**

The three d-spaces given above (Figs 2–4) indicate the variety of forms found among humans in the first week or so of independent locomotion. Each child consistently uses one simple walking form. To find the d-spaces described above (Figs 2–4), we chose three mechanical strategies found among early walkers: twist, gravity, or balance. Each d-space is a simple and extreme example of each type.

The mathematics is based on regions, because each movement is performed differently each time, within limits. Even though each particular example of a movement follows a particular physical trajectory, it is not repeated exactly, so the exact trajectory is not essential to the control of the movement. Each example is specified as a subregion in a many-dimensional space representing walking with a wide-based gait. To use the mathematical definitions correctly, each inclusion has been of a region within a region, getting smaller and more specific at each inclusion (Fig. 8).

Many other forms of early walking mix these three mechanical strategies, as shown schematically in Fig. 9. Besides the real variety in early walking forms, there may be more than one way to denote each movement. There are certainly many ways to perform each movement, both in the freedom assured by using
regions rather than trajectories, and in possible differences in variables parameterizing the movement. There are also other forms of early walking that are not clearly mixes of the Twist, Falling and Stepping walks.

Each d-space has been denoted in some detail, but there is a lot of detail still left out. The d-spaces could be expanded to include head and arm position. They could also be expanded downward to specify regions of force allowing the various movements and muscle activation patterns affording the regions of force.

In the next section, the d-spaces will be abbreviated, to give less rather than more detail. The purpose is to discuss the range of early walking forms and how they may develop into a more mature walking form.

5. Possible Modes of Convergence: The Loss of Variety

The wide variety of early walking forms seems to be lost over the first few months of walking. Adults blend all three mechanical strategies we have described—twisting, gravity and muscle power—in walking. It seems that children also learn to blend these three mechanical strategies within the first few months. Many children who have been walking about 3 months seem to walk with their feet following parallel tracks, hips twisting back and forth like clockwork to move each foot forward in turn. Despite the hip twist, the shoulders only turn enough to counterbalance the hip twist; there is nothing like the exaggerated turn of the Twister. The stride is long enough that some falling motion is present. However, there is clearly controlled balance, with a definite step.

The purpose of this section is to discuss the way the early walking forms blend mechanical strategies as they develop further. We have not done a careful study of the further development of early walking forms. However, we give an abbreviated d-space, approximating the form that may develop after about three months (Fig. 10). The abbreviated d-space is understood to be included in the region of walking forms with a wide-based gait. In the abbreviated d-space, the child avoids vertical movement, as
Abbreviated d-space for a more experienced walker, perhaps a child who has been walking independently for about 3 months. (A) Notation to allow abbreviated d-spaces to be visually simple but still express essential relationships. A cone shape denotes a region of stability or in which the body is erect. A square denotes a region requiring a judgement such as when and where a foot should be put down to break a fall, requiring awareness of time or a variable increasing with time, such as momentum (Fig. 7). A square with missing corners denotes twist of shoulders versus support base (Fig. 5). Arrows denote direction of stability or movement: vertical (arrow up), sagittal (arrow left), or lateral (arrow right). (B) Abbreviated d-space, using the notation from (A), for a walk that includes twist, gravitational propulsion and stepping with balance. The d-space is understood to be included in the region of walks with a wide-based gait. Within that region, the largest region in the abbreviated d-space, at the top, is the region of walks with a wide-based gait that avoid vertical movement (crossed out vertical arrow) and that counter-rotate shoulders and hips, so that the shoulders and hips are always at equal and opposite angles to the forward direction. The counter-rotation is indicated by both a stick figure and a region within a square with missing corners. Included within the region specifying limitations on movement are two phases. The double stance phase is stable, with the support base oriented diagonally to the forward direction. Both double stance and swing phases involve well-coordinated combinations of sagittal and lateral. As the swing foot is brought forward, there is a falling movement toward the other diagonal, indicated by the square that is connected to the cone by a cycle of dashed arrows.

Abbreviated d-spaces for early walking forms

Using the same abbreviated notation, the essential features of the three early walking forms can be extracted from their more detailed d-spaces (Figs 2–4). The abbreviated d-spaces are understood to be included in the region of walking forms with a wide-based gait. Only one stance phase (single or double) and one step phase is given in each abbreviated d-space.

The Twist walk functions essentially by reversing relative trunk twist, the point being to use trunk power to swing each leg around and forward. The Twister’s limitations of motion are summarized as: equal angles, no vertical motion (denoted by a crossed out vertical arrow), and stick figure legs in a plane (Fig. 11A). Double stance is the phase of twisting the trunk, as denoted by a square with missing corners. Double stance alternates, as shown by the dashed arrows, with the phase of swinging each leg around and forward, denoted by a square, because the extent of the swing is limited by the time duration that the child can balance with the leg in the air. The double arrow under the square indicates that instability is in a diagonal direction that changes during the swing.

The Falling walk essentially uses gravity to draw the body down from a precarious erect position and forward, where it is hurriedly caught by the swing foot. The Faller’s major limitation of motion is the lack of lateral movement, indicated by a crossed out lateral arrow (Fig. 11B). The high position is indicated by a stability cone, which is very narrow to indicate precariousness, with an arrow underneath indicating that the fall is in the sagittal direction. The high position alternates, as shown by the dashed arrows, with phases abbreviated into one square, to indicate...
that the limitations of extent and duration of each step are obeyed.

The Stepping walk seems to be a cautious stretching of the bounds of balance. Vertical motion is eschewed, as indicated by a crossed out vertical arrow, and sagittal balance is always maintained, as indicated by the stability cone with a sagittal arrow beneath (Fig. 11C). Double stance is also stable in the right-left direction, as indicated by a stability cone with a lateral arrow beneath, included as one phase under the sagittal stability cone. Double stance alternates, as shown by the dashed arrows, with a stepping phase of lateral falling that obeys the limitations of extent and duration, as indicated by a square with a lateral arrow beneath.

MIXING OF MECHANICAL STRATEGIES

As children learn to mix mechanical strategies, their walking forms lose variety, because all the mechanical strategies are already represented in the variety of early walking forms. The triangle diagram indicating part of the range of early walking forms (Fig. 9) can be extended into a pyramid in time, to show the convergence of early walks (Fig. 12). There may be further energetic, dynamic, physiological, or developmental reasons for the convergence outside the scope of this paper.

Fig. 11. Abbreviated d-spaces for the three extreme walking forms, Twister, Faller and Stepper (Figs 2–4). Notation as in Fig. 10. Abbreviating the d-spaces helps display their essential similarities and differences. Each abbreviated d-space is understood to be included in the region of walks with a wide-based gait. The top region in each abbreviated d-space specifies limitations on movement, as in the fuller d-spaces (Figs 2–4). Within the regions specifying limitations on movement are two phases in each abbreviated d-space: one more still (double stance or, in the Falling case, high position) and one stepping or swing phase. The stepping or swing phase is always denoted by a square, because it always involves some falling movement that requires a foot to be put out to break the fall. The still and stepping phases follow a repeating cycle, as indicated by the dashed arrows. (A) Twister. Limitations on movement are: swing phases must be through equal angles, no vertical movement, and legs in a plane, as indicated by stick figure legs. The double-stance phase is the trunk twist or wind-up phase, denoted by a square with missing corners. The fall of the swing or leg fling phase, indicated by a square, varies in direction in the horizontal plane. (B) Faller. The limitation on movement is lateral. Double stance is not a clear, distinct phase. High position, denoted by a narrow cone, is clear, distinct, and the stillest phase, so it takes the place that double stance occupies in the other abbreviated d-spaces. High position only occurs on one particular foot in the asymmetrical Faller we have considered (Fig. 3). The falling phase represents two swing phases with falling in the sagittal direction. (C) Stepper. Limitations on movement are: no vertical movement, and staying within the stability cone in the sagittal direction. Double stance is also stable in the lateral direction. The fall of swing phase is close to the lateral direction.
forms of early walking converging over the first few months of independent locomotion. Intermediate walking forms, mixing the three mechanical strategies, are generated in the paper from the three extreme forms: Twister, Faller and Stepper. The mixes may be considered as the variety of early walk, used as initial forms of walking by children just attaining independent locomotion (lighter arrows). Also, they may be considered as possible developmental directions, as children approach a more mature and uniform walking form within a few months (heavier arrows).

As the Twister becomes proficient, the stride may lengthen forward, exploiting a bit of fall (Fig. 13; T/F). As in the Twister abbreviated d-space, each step’s twist moves through equal and opposite angles and vertical motion is avoided. The wind-up phase (square with missing corners) is followed by a stepping phase whose fall is modulated: first it is precarious (narrow stability cone) in the sagittal direction and then there is a step in the sagittal direction that obeys the limitations of extent and duration. In this abbreviated d-space, the Twister and Faller strategies may be considered to be converging.

In Fig. 13, the heavy arrows indicate development and convergence, so that Fig. 13(T/F) develops and converges from the Twister and Faller abbreviated d-spaces shown at the top of Fig. 13. Six converged d-spaces are shown. Each converged d-space is a combination of a primary mechanical strategy with a secondary, labelled by the converging modes. The convergent walk described in the previous paragraph is primarily Twister, so the first letter in the label is T. The Twist strategy is augmented by Fall (gravity), rather than simply being limited by it, so the second letter in the label is F.

The convergent walk with Falling primary and Twisting secondary (Fig. 13; F/T) lengthens the falling step with a hip twist. Similarly, a Stepper may add hip twist to lengthen the step, resulting in something like Fig. 13(S/T). Such a walk (Fig. 13; S/T) could also be reached by a Twister adding stability by means of shifting weight to the stance foot, by leaning, by bending the stance knee, by shifting the hips, or by lifting the stance foot. A Stepper may also give up sagittal stability to augment muscle power with gravitational, resulting in something like Fig. 13(S/F). Fig. 13(S/F) is something like the possible more mature walk shown in Fig. 10, but it still lacks the hip twist.

The Twister may learn to keep the head forward, so that the shoulders counter-rotate with the hips. In such a walk, sagittal balance is maintained, and lateral balance alternates with a timed lateral fall, as in a Stepping walk (Fig. 13; T/S). A Faller eventually becomes more balanced, using a broader stability cone, even if the narrow one (high position) is still (temporarily) expedient for propulsion (Fig. 13; F/S).

As the mechanical strategies are mixed, the limitations on motion, such as the Stepper’s strict balance, are relaxed or elaborated. The lateral-vertical-sagittal division of space seems to be relaxed in favor of a walk with twists and diagonal balance which nevertheless moves quickly forward. High guard (the arms being held high) seems to be lost first, then the individual walking form.

6. Discussion

This paper presents the early weeks of walking as a process of practicing one functional mechanical strategy and then integrating other mechanical strategies with the first one. Many mechanical strategies, such as an overhand versus an underhand throw or an ankle versus a hip movement as a fast postural adjustment, are chosen for particular advantages they confer in the circumstances. In contrast, a child in the early weeks of walking is likely to only use one mechanical strategy, and to modify it as more physical principles are integrated; the variety in early walking forms is not in one child but in the set of all children.

Because a mechanical strategy can be implemented by a range of specific trajectories not just by particular-
exact values of each variable the mechanical strategies have been presented in terms of d-spaces, mathematics designed to specify ranges of physiological opportunity. Rather than having to choose particular parameter values that are wrong in almost all cases, the formalism is based directly upon physical principles. Three forms of early walking have been specified in detail as d-spaces in this paper, an indication of the variety of walking forms occurring in the first few weeks of independent locomotion. These are extreme types, not intended as a categorization. Rather than specifying particular physical trajectories, d-spaces allow the representation of the form—including sequence and pattern—of a walk. Within the form of a walk, there is room for the normal variation that most movements display.

How can early walking forms and their underlying mechanical strategies be distinguished experimentally? It would be reasonable to try a similar range of techniques to that used to distinguish postural adjustment strategies, as described in the introduction. One would expect some aspects of muscle activation patterns to differ, depending upon the mechanical strategy, as they do in postural adjustments (Horak & Nashner, 1986). Also, appropriate kinematic measurements would be expected to distinguish the different mechanical strategies, as they do postural adjustments (Shupert et al., 1988, 1992). Torque and shear forces exerted on the support surface may also show characteristic patterns. Studies of intersegmental dynamics, such as have been done for postural adjustment (Gordon, 1990; Kuo & Zajac, 1993) and

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**Fig. 13.** Walking forms with mixed mechanical strategies, generated from the three extreme forms, Twister, Faller and Stepper, and specified as abbreviated d-spaces. Notation as in Figs 10 and 11. The abbreviated d-spaces for Twister, Faller and Stepper (Fig. 11) are given across the top. Heavy arrows connect each of these extreme forms to the four mixed forms generated from it. Each mixture is labelled by two capital letters with a slash, for example, “T/F”. The first letter is the primary form, Twist (T), Fall (F) or Step (S). Most mixed d-spaces have most of the movement limitations of the primary form’s abbreviated d-space. A secondary mechanical strategy is added in each mixture to augment the step, as indicated by the second letter. Further details are given in the text.
for infant kicking (Schneider et al., 1990), would be expected to show differences among mechanical strategies, especially the trunk and leg dynamics.

As a representation of the integration of further mechanical strategies, mixes of the three extreme types are generated in Section 5. Although the method of generation is presented as a development away from the three extreme forms, it also fits the criteria given in Section 3 for generating a wide variety of early walking forms: the generated forms are simple, they assume that the child uses the form consistently, and the mode of generation is by separable components.

The lack of postural control has been hypothesized to be the controlling factor in early gait characteristics (Bril & Brenière, 1993). Postural adjustment strategies develop in the months leading up to independent locomotion and change as the child practices walking (Sveistrup & Woollacott, 1995). Each of the three extreme forms of the early walking considered in this paper requires a different (but overlapping) set of postural control mechanisms. For example, right-left stability is more at risk in the falling form than in the twisting form. The necessary match between mechanical strategies and postural control strategies suggests that they are both equally the controlling factor, with the match between them being the essential feature.

It is interesting to note that these three early walking forms and their mechanical strategies correspond to three different modes of vestibular sensation. The Twister rotates the head horizontally. The Faller’s head follows a vertical falling trajectory, with a fast rise at the end. The Stepper’s head moves as little as possible, and more slowly than the Twister’s or the Faller’s.

The detail allowed by d-spaces in describing movement forms allows an approach to questions about the relationship of regions to physiology, for example of peripheral sensation. Is each of the three early walking examples controlled in a radically different way? How might such differences have arisen, and how might they continue to appear in further development? The d-space formalism—a mathematical language with notation and syntax—allows not only a presentation of the variety of early walking forms according to the relevant variables, but also an analysis of the way the nervous system organizes complex movement control and the development of skills.

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