Movement Models from Sports Reveal Fundamental Insights into Coordination Processes

Keith Davids,[1] Ian Renshaw,[2] and Paul Glazier[3]

[1]University of Otago, Dunedin, New Zealand; [2]Auckland University of Technology, Auckland, New Zealand; and [3]University of Wales Institute, Cardiff, Wales

DAVIDS, K., I. RENSHAW, and P. GLAZIER. Movement models from sports reveal fundamental insights into coordination processes. *Exerc. Sport Sci. Rev.*, Vol. 33, No. 1, pp. 36–42, 2005. *Trends for studying coordination and control have shifted from simple movement models toward complex, multijoint actions in sports such as cricket. Use of such movement models exemplifies the nature of interacting constraints that shape emergence of coordination and control processes as proposed by dynamical systems theory and ecological psychology.* **Key Words:** interacting constraints, coordination, control, perception, action, cricket

INTRODUCTION

Increasingly, a rich range of sports and physical activities are providing models for developing theoretical insights into how processes of perception and action support movement coordination and control. Traditionally, study of motor behavior has been biased away from multijoint actions prevalent in sports and physical activities because of a perceived dichotomy between experimental rigor and ecological validity. Such distinctions are now recognized as part of a continuum, because of advances in technology and the influence of a theoretical paradigm for studying movement coordination and control, dominated by ecological psychology (7) and dynamical systems theory (8). *Inter alia* movement models such as hula hooping, javelin and discus throwing, and rowing have become increasingly popular with movement scientists (1,3,14). In this review, we identify theoretical reasons for changes in selection of movement models for studying coordination and control, arguing that sports and physical activities provide relevant task vehicles because they exemplify how processes of perception and action: (a) are mutually enabling, (b) are embodied within the performer-environment system, (c) function in a task-specific manner, and (d) are dependent on nested, interacting constraints inherent to particular performance contexts. To achieve our aim, we analyzed research in cricket, a sport replete with relevant movement models such as dynamic interceptive actions like catching, batting, and locomotor pointing (running toward a target in space).

A UNIFIED FRAMEWORK FOR STUDYING BEHAVIOR OF BIOLOGICAL MOVEMENT SYSTEMS

Ideas from dynamical systems theory and ecological psychology characterize biological movement systems as complex, dynamical systems, revealing how the composite motor system degrees of freedom are coordinated and controlled during interactions with the environment (8). Coordination emerges between components of dynamical movement systems through processes of self-organization ubiquitous in natural physical and biological systems. Interest especially has centered on phase transitions (movements of system microcomponents into different states of organization) that can occur spontaneously in natural dynamical systems, because they provide windows for understanding how coordination emerges in biological movement systems. Dynamical systems exploit surrounding constraints to allow functional, self-sustaining patterns of behavior to emerge in specific contexts. In dynamical movement systems, this process modifies the number of biomechanical degrees of freedom regulated by the performer through the temporary assemblage of muscle complexes called *coordinative structures*. Variability in movement patterns, exemplified by fluctuations in stability, permits flexible and adaptive motor system behavior, and the paradox between stability and variability explains how skilled athletes can produce a subtle blend of persistent and adaptive

movements during successful performance (4,5). For motor behavior specialists, the radical implication of these ideas is that perceptions, memories, intentions, plans, or actions may be conceived of as emergent, self-organizing, macroscopic patterns formed by the interaction of the molecular constituents of the neuromusculoskeletal system.

Increasing attention on movement models in sports and physical activities also owes much to theoretical concepts from ecological psychology (6). Adopting a systems perspective, ecological psychologists emphasize the organism–environment system as the unit of analysis for studying perception and action in natural environments. It is argued that biological organisms are surrounded by huge arrays of energy that can provide information (*e.g.*, optical, acoustic, proprioceptive) to constrain movement behavior, including decision making, planning, and organization (2,6,7). The structure of energy carries information for a performer that is specific to certain contexts and that is available to be perceived directly. For example, light reaches the eyes of a cricketer after having been reflected off surfaces (*i.e.*, the pitch) and moving objects (*i.e.*, the bowler and the ball). According to ecological psychology, the use of information to support movement requires a law of control that continually relates the state of the individual to the state of the environment. That is, individuals establish a relationship with the environment leading to a law of control relating a kinematic property of a movement to a kinematic property of the perceptual flow (9). Ecological psychology seeks to understand the nature of the perceptual variables that can be used to regulate movement. To detect perceptual information, a significant role is attributed to specific movements of the performer and relevant environmental objects. Movements cause lawful changes to energy flows that provide information on environmental properties to performers. Consequently, task vehicles from sports can provide valuable insights into: (a) the nature of perceptual information used to constrain action, and (b) the inextricable relationship between information and movement in specific performance contexts. Traditional experimental tasks have been useful in identifying lower-order variables (*e.g.*, target location, velocity, and acceleration) when investigating perception under controlled laboratory conditions (2). However, traditional (*e.g.*, psychophysical) approaches for studying perception and movement are rather reductionist, located in static movement models and favoring a 'fine-grain' perspective. Growing preference for movement models from sports and physical activities reflects these criticisms, emphasizing a more functional view characterizing the intrinsic and inescapable link between perception and the control of natural movements. This more coarse-grained perspective focuses on higher-order perceptual variables at the level of the performer–environment system, increasing understanding of the different ways in which perceptual processes function during natural movements (14).

The tendency to use movement models from sports to study coordination and control is not universal, and dynamical systems theorists themselves have been criticized for selecting task vehicles perceived to be isolated from real life (14). For example, the selective use of contrived laboratory tasks involving finger, wrist, and arm rhythmical movements by dynamicists seeking empirical support for abstract laws to characterize movement systems components as nonlinear-coupled oscillators has been criticized. Nevertheless, a process-oriented, time-continuous approach motivated by investigation of coordination dynamics of rhythmical, segmental interactions has been transferred successfully to the study of movements in sports and physical activities (14). A major reason for this successful crossover has been the goal of studying processes of self-organization under interacting constraints, and sports and physical activities are rich in movement models exemplifying how neuroanatomical, intentional, task, and environmental constraints shape emergence of coordination and control (4). In the following section, cricket is highlighted to exemplify how its movement models provide a rich backdrop for the study of coordination and control processes.

MOVEMENT MODELS IN CRICKET ARE A WINDOW ON COORDINATION AND CONTROL PROCESSES

Cricketers require skill in a variety of complex, multijoint, interceptive actions when batting, bowling, and fielding. The spatiotemporal task constraints of cricket are demanding; for example, batting requires interception of a ball with typical trajectory times ranging from approximately 1 to 0.6 second. Skilled cricketers, facing fast bowling speeds of 160 km·h^{-1}, need to discriminate perceptually the spatial trajectories in depth of balls to a precision of 0.5°. Response timing precision in cricket batting has estimated margins of failure of approximately ±2.5 ms at the point of movement execution. When fielding, players perform one- and two-handed catches of the ball, with error margins for timing the grasp phase of approximately 16 ms.

Prospective Control of Interceptive Actions in Cricket

How do cricketers satisfy such severe spatiotemporal task constraints? In these tasks, it has been shown that perceptual information from the environment guides spatiotemporal patterning of appropriate limb(s) and striking implements to intercept a target or surface.

Although traditionally it was believed that performers use information to predict how to get the catching hand in the right place at the right time, ecological psychology has provided prospective control models to demonstrate how such stringent task constraints are satisfied (2,9). In prospective control models of interceptive actions, the performer establishes a relationship with key perceptual variables in the environment to regulate actions continuously. Prospective control has inherited its theoretical foundations from ecological psychology, which emphasizes that an important task constraint is the information available in specific performance contexts for performers to use in coordinating actions with respect to the environment (4). Empirical studies of prospective control have shown how perceptual variables from ball motion are coupled to movements and used to regulate the spatiotemporal patterning continuously of even the most rapid of interceptive actions. For example, time to contact (TC) and place of contact have been identified as examples of higher order, constraining perceptual variables

available for prospective control of action during catching and batting (2). These two candidate perceptual variables describe how the catching hand can be moved to the right place at the right time. These ideas emphasize how, in sport, learners can establish relations with specific environments (*e.g.*, different sport contexts). Because energy flow patterns are specific to particular environmental properties, they can act as invariant information sources to be picked directly by individual performers to constrain their actions. Learning in sport concerns the attunement to information in specific contexts and the construction of functional relations between movement and information, providing information–movement couplings underpinned by laws of control (exemplified below) (2). Jacobs and Michaels (7) argued that there are two processes involved when learners assemble information–movement couplings. First, learners educate attention by becoming better at detecting the key information variables (*e.g.*, TC and place of contact) that specify movements from the myriad of variables that do not. During practice, they narrow down the minimal information needed to regulate movement from the enormous amount available in the environment. Second, learners calibrate actions by tuning movement to a critical information source (*e.g.*, TC and place of contact) and, through practice, institute and sustain information–movement couplings to regulate behavior.

## Catching Behavior: Getting in the Right Place at the Right Time

Prospective control of timing behavior during one-handed ball catching is exemplified when a performer determines the required velocity of hand movement from perceptual variables in the environment (equation 1) (10). Equation 1 demonstrates that performers are able continuously to use information to match the velocity required to intercept a ball. In equation 1, required velocity is expressed as the ratio of current lateral distance (*i.e.*, distance between the hand and the ball's projection plane onto the hand-movement axis) to the first-order TC between the ball and the hand-movement axis. Factors on the right-hand side of equation 1 (*i.e.*, the velocity differential) can be specified optically by monocular and binocular (lower-order) perceptual variables. Equation 2 shows how perception of required velocity of the catching hand can be coupled with interceptive movements as the performer modulates the hand's acceleration based on an optically specified velocity differential:

$$\dot{X}_{h\ req} = \frac{X_h - X_b}{TC_1} \tag{1}$$

and

$$\ddot{X}_h = \alpha \, \dot{X}_{h\ req} - \beta \, \dot{X}_h, \tag{2}$$

where $\ddot{X}_h$, $\dot{X}_{h\ req}$, and $\dot{X}_h$ are the hand's current acceleration, current required velocity, and current velocity, respectively, and α and β are constants, and where X_h, X_b, and TC_1 are the hand's current position, the projection of the ball's current position on the hand-movement axis, and the first-order TC between the ball and the hand-movement axis, respectively. Figure 1 captures the capacity of the performer to

$$\dot{X}_{h\ req} = \frac{X_h - X_b}{TC_1(Z)}$$
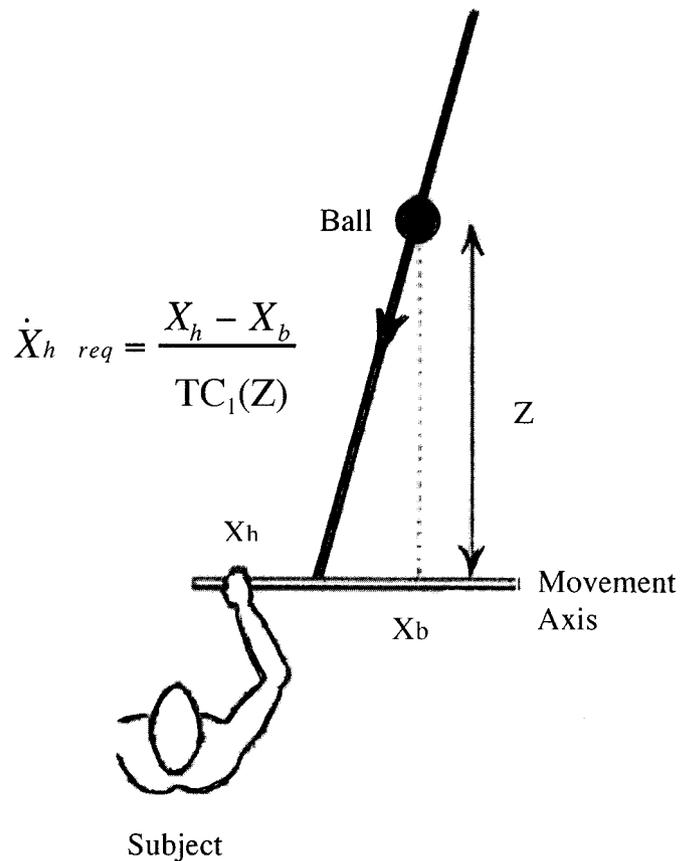
Figure 1. Establishing a meaningful relationship with the environment during one-handed catching: a graphic illustration of how equations 1 and 2 capture the way that successful catchers modulate movement acceleration to produce a tight fit between current and required velocity of the hand. [Adapted from Montagne, G., M. Laurent, A. Durey, and R.J. Bootsma. Movement reversals in ball catching. *Exp. Brain Res.* 129:87–92, 1999. Copyright © 1999 Springer. Used with permission.]

establish a relationship with the environment in picking up and using optical information to adjust hand positioning continuously relative to a moving ball, when necessary. It illustrates how prospective control strategies can supersede traditional predictive control models for interceptive actions in sport. Recent data support the use of this law of control, and the model's validity was supported by experimentation in which current lateral distances between ball and hand were manipulated to observe influence on hand acceleration (10). Individuals caught balls approaching a standard interception point from different initial start points. Use of a prospective strategy predicts that even when the hand is positioned at the point of interception, individuals would start by moving their hand to fill in the lateral distance, before changing direction to catch the ball (causing a movement reversal). This idea was supported by observations of a significant number of movement reversals for balls approaching on trajectories curving inward or outward, compared with a straight pathway (approximately 60% of all trials), with the hand being moved at the required velocity approximately 300 ms before interception. Movement reversals are not superfluous, and support prospective control of interceptive actions, because they exemplify how performers can use movement to create constraining information for successful performance (4,10).

When Two Hands Are Better Than One

Movement models from cricket also can deepen understanding of bimanual coordination. For example, slip fielders standing behind the batsman often use two hands to catch a ball approaching them at high velocity when it is deflected from the edge of the bat. Task constraints used to study two-handed actions, such as slip fielding, belong to two main categories: (a) hands moving symmetrically and simultaneously, and (b) hands moving asymmetrically and simultaneously. Furthermore, task constraints requiring two hands to perform discrete, object-oriented, goal-directed actions are underrepresented in the bimanual coordination literature (11). Slip fielding is an ideal movement model for studying two-handed catching because both hands are coupled asymmetrically in an isodirectional movement to intercept a ball, although it has been investigated rarely. An exception to this trend was a study of two-handed catching behavior under similar task constraints to slip fielding (15). Data showed that skilled catchers formed a coordinative structure in which the two hands adhered to a common timing structure to ensure synchronized time of arrival at a perceived interception point from spatially variable initiation points. When one hand needed to travel farther than the other hand to the perceived interception point, it traveled faster to synchronize time of arrival. Movement initiation time data revealed that the limbs began to move at identical moments in time from varying distances apart. Despite the left and right limbs having to move farther because of different spatial projections of the ball, both limbs set off at the same time: movement initiation time, 208 (±18) ms, 204 (±22) ms, and 196 (±30) ms. Velocity and acceleration data also showed how the two hands formed a coordinative structure to achieve the interception goal. The two limbs showed a synchronous pattern throughout the entire movement, with the largest interlimb difference for time-to-peak velocity being 5 ms, and the largest interlimb difference in time-to-peak acceleration being 6 ms (see Fig. 2A, B). The slip-catching problem is solved by the performer integrating upper limb degrees of freedom into a single coordinative structure for bimanual coordination, which preserves symmetry of the two-handed catch by maintaining important asymmetries in limb movements. Timing is the essential variable (a variable reflecting behavioral organization of two-handed catching) preserved by slip fielders in cricket to synchronize time of arrival of both hands at the point of interception. This study showed that a common timing structure, synchronizing velocity and acceleration of both hands, was superimposed as the limbs exploited asymmetries in limb movement speeds to approach the ball from asymmetrical start points.

Coordination Modes Emerge Under Practice Task Constraints

Two-handed tasks such as slip fielding and batting often are practiced with the use of ball projection machines, and research on cricket batting has raised important questions on their role in fine-tuning processes of perception and action. As we noted earlier, perception is specific to environmental properties uniquely constraining each performance situation, and changing the ecological constraints of practice can

(a) Velocity
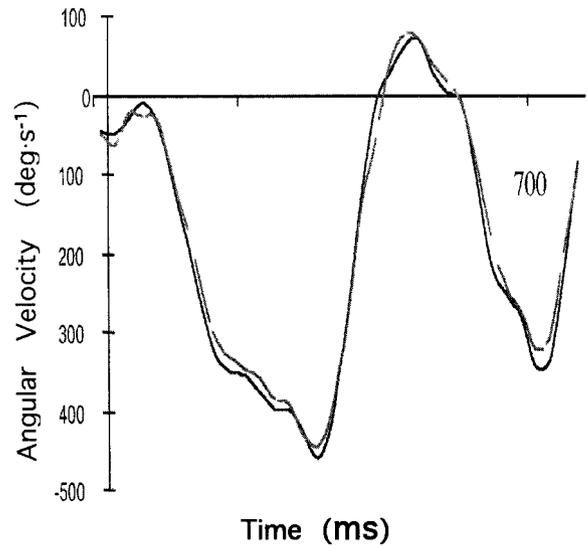
(b) Acceleration
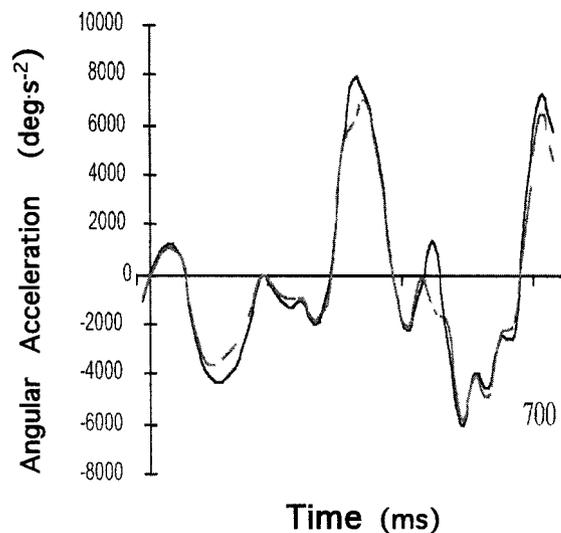
Figure 2. The velocity and acceleration traces for a single participant performing a two-handed catch projected to the center of the chest area. The dashed gray line represents the right arm, and the solid black line represents the left arm. [Adapted from Tayler, M.T. Bimanual coordination in catching behaviour. In: *Interceptive Actions in Sport*, edited by K. Davids, G. J. P. Savelsbergh, S. J. Bennett, and J. Van Der Kamp. London: Routledge, 2002, p. 242–258. Copyright © 2002 Thomson. Used with permission.]

significantly influence the movement behaviors that emerge (2). It follows that learners need to be educated to pick up constraining perceptual variables rather than nonconstraining (less relevant) variables in specific and relevant practice

contexts (7). However, practice environments traditionally have been adapted to manage information loads on learners through decomposition of key tasks into microcomponents. For example, in cricket, bowling machines allow accurate and stable projection of balls to enable acquisition of batting skill in isolation from game contexts. When using bowling machines, good coaches attempt to replicate match conditions by randomizing the angle of ball release to reflect the variability of real bowlers. However, batters in cricket can gain a temporal advantage by using preflight information from body orientation and limb segments of bowlers as they deliver the ball. Through attunement to this body action information, batters can make early predictions on the direction and bounce point of the delivery, as well as the type of spin placed on the ball. Given these differences in ecological constraints, an interesting question is whether batting under the different task constraints of a bowling machine (BM) or real bowler (B) alters coordination of the forward defensive (a shot used to stop a ball from hitting the batter's wicket, requiring the batter to step forward toward the oncoming ball and place the bat alongside the lower leg, forming a barrier to prevent the ball from hitting the stumps). We examined temporal organization of the forward defensive stroke played by batsmen of high intermediate standard from the moment of ball release (*i.e.*, the machine projection mouth or the bowler's hand) up to the point of ball–bat contact (velocity, 26.76 m·s^{-1} under both conditions) (4). Data generally showed specificity of coordination and timing under these different ecological constraints. Against the BM, stroke backswing was coupled to moment of ball release (0.02 ± 0.10 s); against B, the backswing started later (0.12 ± 0.04 s). Initiation of the front foot movement occurred later (0.16 ± 0.04 s after ball release) in the bowling machine condition compared with facing the bowler (0.14 ± 0.03 s after ball release). Initiation of stroke downswing commenced earlier when facing BM compared with B (0.32 ± 0.04 s compared with 0.41 ± 0.03 s). A different ratio of backswing–downswing was observed when batting against BM compared with B (see Fig. 3). Timing of the placement of the front foot against BM was similar against B (0.53 ± 0.05 s compared with 0.55 ± 0.05 s). Peak bat height differed under the two task constraints (BM, 1.56 ± 0.2 m; B, 1.72 ± 0.1 m). Mean length of front foot stride was shorter against BM (0.55 ± 0.07 m) compared with B (0.59 ± 0.06 m). Correlation between initiation of backswing and front foot movement was much higher against B ($r = 0.88$) than BM ($r = 0.65$). In summary, results suggested that practice conditions against projectile machines contain different informational constraints than practicing against real bowlers. Use of real bowlers to deliver the ball allows batsmen to attune to relevant constraining perceptual variables from body movements before ball release, and avoids coupling movement to nonconstraining variables not present in performance conditions.

Running Toward Targets: Cricket Bowling Run-Ups

As well as fielding and batting, many cricketers are required to bowl in a match, which involves running toward a target area to deliver a ball overarm, placing part of the front foot behind the front line or popping crease to avoid bowling a no-ball. The run-up in cricket bowling is an example of
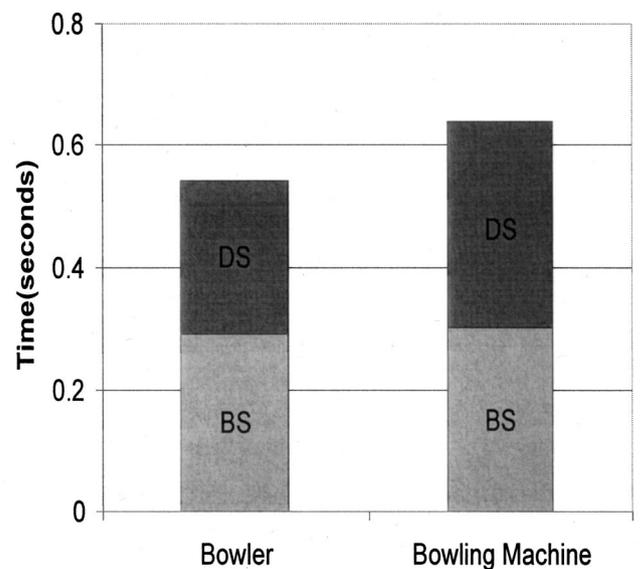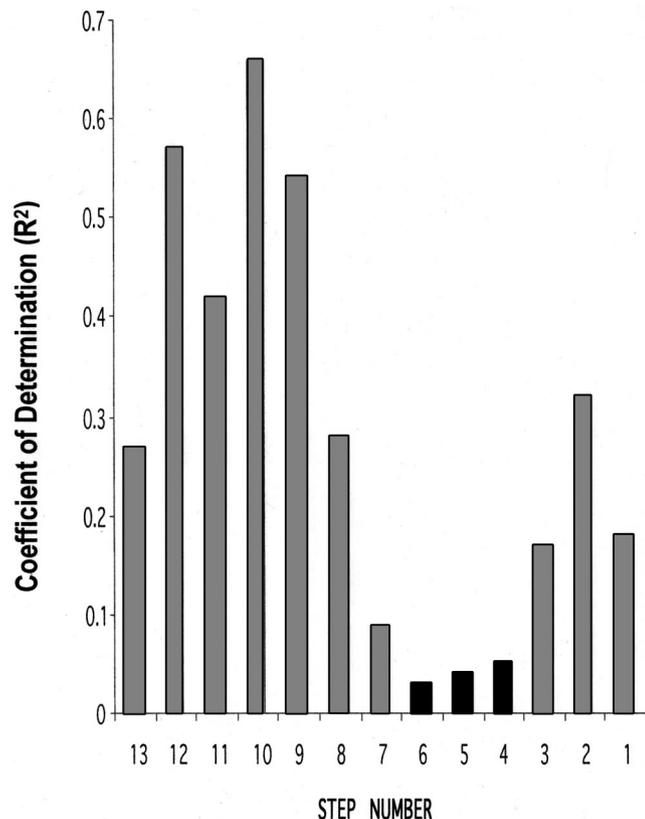

Figure 3. Ratio of backswing to downswing in the bowler and bowling machine conditions. The total time length for bat swing is greater in the bowling machine condition, with the ratio of backswing to downswing in the bowler condition being 47:53, whereas in the bowling machine condition, the ratio is 54:46.

locomotor pointing, a movement model that has been studied extensively in experiments on perception and action during goal-directed gait. Important questions concerning the control mechanisms and information sources used to regulate gait during locomotor pointing and a prospective control model have been proposed to explain visually driven adaptations of locomotion (13). As in prospective modeling of catching behavior, if information on current and required behavior were optically available, then regulation of gait might be based continuously on perception of the difference between them. In the model, a nervous system central pattern generator controls basic gait patterns, which are instantaneously adapted during locomotor pointing through modulation of a key gait parameter, step length. Computer simulation testing of the model showed: (a) a marked decrease in toe-target distance variability in the last few steps of a locomotor pointing task, and (b) that the greater the adjustment needed during approach to a target, the earlier visual regulation of steps began.
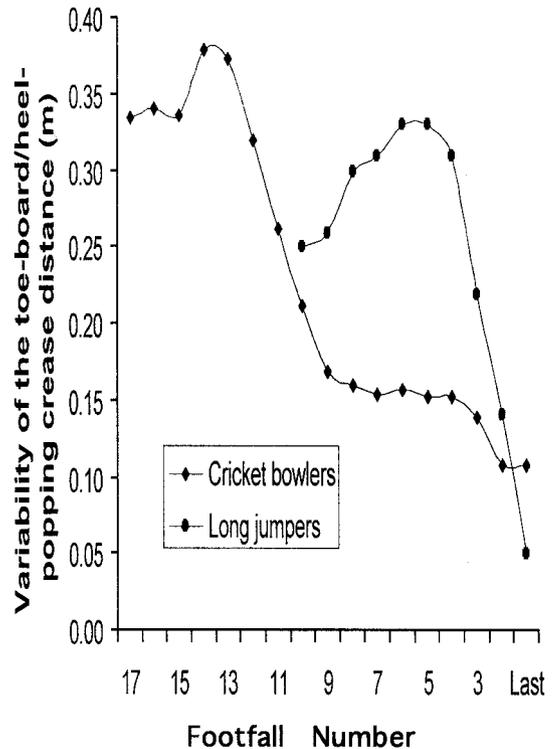
A number of task vehicles in sports readily lend themselves to behavioral tests of the locomotor pointing prospective control model, including approach running in the athletic jumps, javelin throwing, and gymnastic vaulting. A behavioral study of the long jump run-up confirmed that locomotor pointing was a direct function of the optical flow generated by performers, and that the onset of stride length adjustment was a function of the amount of adjustment required (9). But an important source of constraint in natural locomotor pointing tasks is nested actions at the end of an approach run. Some tasks, like the horizontal jumps and gymnastics vaulting, require generation of maximum velocity during the run-up to hit the takeoff board, whereas others require a more controlled collision with a target area because of the need for further complex actions nested on the approach phase. Cricket bowling is a task in which speed versus accuracy

tradeoffs are required, being composed of four phases: run-up, bound, delivery stride, and follow-through. The run-up enables the bowler to move into the bound phase, maintaining momentum gained and positioning the body effectively for a successful link to the delivery stride. The bound stride is the stride that links the run-up to the delivery stride. During the bound phase, the bowler aims to jump forward, high enough to land in the correct position for the delivery stride to release the ball with the desired velocity by manipulating the angle and speed of ball delivery. Clearly, horizontal velocity generated in negotiating the bound phase needs to be managed carefully. A controlled arrival at a target area emphasizes early initiation of visual regulation because step adjustments can be spread evenly over more strides, causing less disruption to nested actions by excessive horizontal velocity of the approach phase.

Our analysis of run-ups of professional cricketers revealed support for the prospective control model of locomotor pointing (12). A combination of interstep and intrastep analyses on the run-ups of cricketers showed that, because of nested constraints of cricket bowling, most of the bowlers made adjustments early in the run-up, before making late adjustments just before the bound stride (see Fig. 4). Almost all run-ups were regulated at some stage (91 of 92), and

Figure 5. Data from the run-ups of skilled cricket bowlers and long jumpers showing how different task constraints nested at the end of the approach phase can constrain the variability of footfall placement. In cricketers, visual regulation occurred at different phases of the run-up, as and when necessary, whereas the extensive approach velocity of the long jumpers constrained visual regulation to occur less frequently. Data on cricket bowlers from (12); data on long jumpers from (9).

regulations were spread over the entire length of the run-ups, in contrast to long jumpers (see Fig. 5). Few correlations were found between stride number and the amount of adjustment, as reported in studies of long jumpers. The inconsistent starting points of the bowlers and the initial high levels of variability did not prevent them from achieving remarkably low levels of variability at the bound stride, consistent with data from long jumpers. To achieve such functional levels of footfall variability at the critical bound stride, bowlers were making adjustments based on need at very early stages of the run-up (*e.g.*, 20 m from the popping crease), a finding in line with a key premise of prospective control models: that regulation is continuous, and based on perception of current and required behavior. Data showed that the task constraints of cricket bowling benefited from a greater amount of adaptive visual control during the whole of the run-up, compared with the velocity-generation constraint that dominates the athletic jumps (see Fig. 5).

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Recent preferences for studying movement models from sports and physical activities are a consequence of a renewed diversion away from reductionism in studying processes of coordination and control. In this paper, we described how movement models from the sport of cricket exemplify how

Figure 4. Relationships (R^2) between amount of step length adjustment made and amount needed for each run-up stride for professional cricketers. Data plots reveal that bowlers spread their adjustments over the whole of the run-up as and when required. Nonsignificant correlations are in black. [Adapted from Renshaw, I., and K. Davids. Nested task constraints shape continuous perception-action coupling control during human locomotor pointing. *Neurosci. Lett.* 369:93–98, 2004. Copyright © 2004 Elsevier. Used with permission.]

human movements can be understood in relation to the interacting constraints of structural and functional neuroanatomical design, specific task goals, and environmental contexts. We argued that the transition of complex task vehicles to the forefront of research on human movement behavior has coincided with advances in theorizing from a combined ecological psychology and dynamical systems viewpoint. Movement models from sport, at one time considered trivial in the movement science literature, are proving excellent task vehicles for providing unique insights into how actions are coordinated with respect to environmental objects and events. This approach is signaling a fresh perspective on the role of variability in facilitating adaptation to dynamic task environments. Analysis of behavior at the level of the performer–environment system reveals that coordination modes are examples of natural, emergent phenomena that can be functionally varied to dynamic task constraints.(6)

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