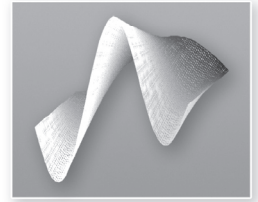


Chapter 3



The Interface of Biomechanics and Motor Control

Dynamic Systems Theory and the Functional Role of Movement Variability

*Paul S. Glazier, PhD, Jonathan S. Wheat, PhD,
David L. Pease, and Roger M. Bartlett, PhD*

Editors' Overview

An integrative perspective provided by the link between biomechanics and motor control is developed in this chapter, and the implications for biomechanical modeling and measurement are discussed in detail. Running and swimming are used to examine the measurement of variability in gait under the different environmental constraints of with and without gravitational forces (swimming is viewed as an aquatic gait). The classic biomechanical method of hierarchical modeling is outlined, and components of the functional pattern of coordination used to achieve locomotion are placed in this integrated schematic to facilitate motion analysis. In analyzing the literature on running gait and overuse injuries, it is shown that variability in coordination during the interval between the initial foot contact and the neutral position of the stance phase is an important feature of normal, healthy running.

The emergence of dynamic systems theory as a viable multidisciplinary framework for modeling the sensorimotor system stimulated a radical reassessment of the concept of movement variability. Traditionally, movement variability has been considered a dysfunctional aspect of human motor behavior directly related to the amount of noise—random fluctuations that compromise the deterministic

relation between input and output at different levels of description—in the sensorimotor system (Newell and Corcos, 1993; Slifkin and Newell, 1998). However, the introduction of nonlinear dynamics and chaos theory into the study of biological systems (see Glass and Mackey, 1988; Thompson and Stewart, 2002) has prompted motor control theorists to suggest that movement variability may occupy a functional role in human motor behavior. Indeed, recent evidence from research based on dynamic systems theory strongly supports the notion that movement variability is an essential feature of human motor behavior that affords the sensorimotor system the necessary flexibility and adaptability to operate proficiently in a variety of performance, development and learning contexts (see van Emmerik & Wagenaar, 1995; Newell & Slifkin, 1998; van Emmerik & van Wegen, 2000, 2002; Latash, Scholz, & Schönner, 2002; Piek, 2002; Riley & Turvey, 2002; Davids, Glazier, Araújo, & Bartlett, 2003 for comprehensive reviews).

Movement Variability: Traditional and Contemporary Approaches

One of the main reasons for this change of ethos is the shift in the experimental paradigms motor control theorists use to study motor behavior. In cognitive science, empirical studies have been dominated by outcome measures obtained from sensorimotor tasks requiring the use of a single biomechanical degree of freedom (Newell, 1985). These artificial tasks have typically been favored by proponents of information processing because they enable theoretical inferences about underlying hierarchical control structures such as schemas, programs, and representations (Davids, Handford, & Williams, 1994). As movement variability cannot be directly determined from these tasks, it has often been inferred from the variability of outcome measures such as accuracy or error scores (Schmidt & Lee, 1998). The general assumption is that the variability of outcome measures is accompanied by a similar amount of variability in the movement patterns that produced the outcome measures (Newell & Corcos, 1993). As skilled motor performance is often characterized by low variability of outcome measures (e.g., Anderson & Pitcairn, 1986), it follows that skilled motor performance is also characterized by highly consistent patterns of movement. Therefore, movement variability has been considered as a problem in the sensorimotor system that should be minimized or eliminated.

It has become apparent, however, that these experimental paradigms may have contributed to the negative connotations of movement variability in human motor behavior. As sensorimotor tasks requiring the use of a single biomechanical degree of freedom eliminate the problem of coordination at the behavioral level of analysis (Newell, 1985, 1986), it is reasonable to assume that the variability of outcome measures directly relates to the variability of the accompanying patterns of movement. However, under different task constraints such as those encountered in tasks requiring the use of multiple biomechanical

degrees of freedom, it has been found that the variability of outcome measures does not necessarily relate to the variability of the accompanying patterns of movement. For example, in the frequently cited studies by Arutyunyan, Gurfinkel, and Mirskii (1968, 1969) investigating the accuracy of aiming in pistol shooting, it was found that compensatory movements of the arms enabled skilled marksmen to reduce the variability in the spatial orientation of the pistol barrel. In contrast, novice marksmen were unable to demonstrate such compensatory movements and therefore exhibited greater variability in the spatial orientation of the pistol barrel. Under these task constraints, movement variability needs to be interpreted carefully in relation to specific task goals rather than be dismissed as random fluctuations that lead to variability in the performance outcome.

In contrast to the experimental paradigms used in cognitive science, the theoretical approach of dynamic systems to motor behavior places greater emphasis on the space-time characteristics of coordination patterns in tasks requiring the use of multiple biomechanical degrees of freedom. In dynamic systems theory, patterns of movement emerge through generic processes of physical self-organization rather than being prescribed by some sort of executive regulating agent (Kelso, 1995). A central tenet of this theoretical approach is the spontaneous formation and dissipation of coordinative structures or functional synergies in response to changes in energy surrounding the sensorimotor system (Kugler, Kelso, and Turvey, 1980, 1982). Kay (1988) has defined these task-specific units as “an assemblage of many micro-components . . . assembled temporarily and flexibly, so that a single micro-component may participate in many different coordinative structures on different occasions” (p. 344). As the morphology of these coordinative structures entirely depends on the internal and external constraints acting on the sensorimotor system (Higgins, 1977; Kugler, 1986; Newell, 1986; Clark, 1995), the space-time characteristics of the ensuing patterns of coordination not only provide insight into these constraints, but also into the state of the dynamics of the sensorimotor system at that specific moment (McGinnis & Newell, 1982).

Therefore, proponents of dynamic systems have sought to identify observable low-dimensional macroscopic variables—the so-called order parameters (Haken, 1983)—that define stable and reproducible relationships occurring among the components of the sensorimotor system as it searches for and adopts functionally preferred states of coordination or attractor states (e.g., Kelso & Schöner, 1988; Kelso & Ding, 1993). At the behavioral level of description, these order parameters are typically kinematic measurements such as displacements, velocities, and accelerations or are electromyographic measurements and other variables, such as relative timing, that are derived from these biomechanical measurements (e.g., Scholz, 1990). It has been shown that when the sensorimotor system adopts a functionally preferred state of coordination, the dynamics of order parameters are highly ordered and stable, reflecting the capacity of the sensorimotor system to produce consistent patterns of coordination (Kelso,

1984; Haken, Kelso, & Bunz, 1985). It has also been shown that variability in the dynamics of the order parameters, exemplified by fluctuations in stability, reflects the capacity of the sensorimotor system for flexible and adaptive behavior that can tailor patterns of coordination to specific environmental and task demands (Kelso, 1997). As the internal and external constraints—acting as the so-called control parameters (Haken, 1983)—increase toward a critical value, fluctuations in stability increase until stability is lost, leading to a non-equilibrium phase transition or bifurcation and the adoption of a new attractor state. Clearly, these empirically-derived findings suggest that movement variability is a functional entity that facilitates the discovery and adoption of optimal states of coordination.

Biomechanics and Motor Control

It would appear from the literature that the integration of biomechanical measurement tools and data collection techniques has substantially contributed to the discovery and monitoring of order parameters, the subsequent mapping of attractor states in different control spaces, and the redefinition of movement variability as a functional entity rather than simply noise in the sensorimotor system. In addition to describing the motion of the components of the sensorimotor system, biomechanical modeling techniques have also been used to investigate the mechanisms that physically cause this motion (see Zernicke & Schneider, 1993; Kamm, Thelen, & Jensen, 1990 for comprehensive overviews). For example, Thelen and colleagues (e.g., Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990; Thelen, Zernicke, Schneider, Jensen, Kamm, & Corbetta, 1992; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Thelen, Corbetta, & Spencer, 1996; Thelen, 1998) used the inverse dynamics¹ approach to examine the influences of active and passive joint torques and forces on the reaching and grasping of young infants during their first year of life. Active joint torques and forces were considered to be those that were generated primarily by muscle action, whereas passive joint torques and forces included gravitational force, frictional forces and torques within the joint, and inertial forces and torques transferred from other body segments. Thelen and colleagues found that the infants became more adept at managing the complex interplay between active and passive joint torques and forces with skill acquisition. Furthermore, they found that passive joint torques and forces were used more effectively as skill was acquired, and thus the dependence on active joint torques and forces decreased. Similarly, Schneider and Zernicke (1989) and Schneider, Zernicke, Schmidt, and Hart (1989) used the inverse dynamics

¹ The term *dynamics* has two very different meanings in dynamic systems and biomechanics. In dynamic systems theory, *dynamics* refers to the time evolution of a system at any level of description whereas in biomechanics, *dynamics* refers to the forces and torques that physically cause motion (Beek, Peper, & Stegeman, 1995).

approach to examine the relative influences of active and passive torques and forces in the learning of a task requiring rapid arm movement. They found that with practice, active torques and forces complimented and counteracted passive torques and forces more effectively, particularly during movement reversals. The increased effectiveness helped hand velocities and accelerations to increase, hand trajectories to become smoother and more parabolic, and total movement times to decrease. Both of these studies empirically support Bernstein's (1967) hypothesis regarding the exploitation and utilization of reactive phenomena as an advanced feature of skill learning (e.g., Newell and Vaillancourt, 2001).

Despite the important contributions of biomechanics to the study of motor behavior, development and learning, biomechanics has not experienced the same degree of reciprocity, particularly in sport biomechanics. Although the theoretical concepts and methods of the study of dynamic systems were extensively covered in the scientific literature over the past decade, their huge scope and potential have yet to be fully realized by sport biomechanists and have rarely been integrated into research on sport biomechanics. It could be argued that sport biomechanists have so far missed an important opportunity, especially considering recent criticisms of applied sport biomechanics for (i) being too descriptive (Vaughan, 1984; Norman, 1985; Baumann, 1987; Cavanagh, 1990; Yeadon & Challis, 1994; Elliott, 1999), and (ii), for lacking a sound theoretical rationale (Hay, 1983; Bartlett, 1997; Hatze, 1998). Furthermore, it has frequently been suggested that in order to make significant scientific progress, sport biomechanists need to collaborate with experts from other disciplines of sport science (Nelson, 1971; Cavanagh & Hinrichs, 1981; Cavanagh, 1989; Dillman, 1989; Gregor, 1989; Norman, 1989; Winter, 1989; Gregor, Broker & Ryan, 1992; Nigg, 1993; Zatsiorsky & Fortney, 1993; Coleman, 2002; Elliott, 2002; Enoka, 2004). From this perspective, there is a unique opportunity for sport biomechanists to form a mutually beneficial partnership with motor control theorists. Indeed of all the potential interdisciplinary partnerships, this collaboration could be the most fruitful in satisfying the two main goals of sport biomechanics—reducing injury and improving performance (e.g., Baumann, 1987; Nelson, 1989; Elliott, 1997; Nigg, 1998; Bartlett, 1999; Zatsiorsky, 2000).

In this chapter, we explore some of the potential implications of dynamic systems theory and this new view of movement variability for applied sport biomechanics. We have previously argued that this theory provides a relevant framework for performance-related research in sport biomechanics, as it emphasizes an interdisciplinary approach to the processes of coordination and control in the human sensorimotor system (Glazier, Davids, & Bartlett, 2003). Here, we consolidate our previous assertions and extend our analysis to injury-related research in sport biomechanics, using running and swimming—which has been described as the aquatic equivalent of running (Alexander, 1984, 1989)—as vehicles for our analysis. We begin, however, with a critical overview of the philosophical and theoretical paradigms used in performance-related and injury-related research in sport biomechanics.

Sport Biomechanics: A Critical Overview

The main goals of performance-related and injury-related research in sport biomechanics are to identify the characteristics of technique that contribute to successful motor performance or that predispose to injury (Bartlett, 1999). In performance-related research, a combination of theoretical and statistical modeling techniques is often used to identify key biomechanical variables known as performance parameters (Bartlett, 1999; Lees, 1999). The initial development of a deterministic or 'hierarchical' model (Hay & Reid, 1988; Lees, 2002), based on the theoretical principles of biomechanics and the fundamental laws of physics and biology that govern biomechanics (Bunn, 1972; Cooper & Glassow, 1976; Bober, 1981; Hochmuth, 1984), can greatly assist in identifying relationships between the performance criterion (the task goal or outcome) and the underlying performance parameters. A 'hierarchical' model can also be instrumental in helping to establish the causative mechanisms underpinning these relationships.

In the hierarchical model for swimming shown in figure 3.1, the performance criterion (the official swimming time) is identified at the top of the model. As the performance criterion is a temporal measurement, it can be divided into a series of constituents—starting time, stroking time, and turning time—that form the second tier of the model. The final stage of model development is to identify the performance parameters that underpin each of the constituents of the performance criterion. As stroking time is the most important of these constituents, we have only included its underpinning performance parameters for the sake of brevity. There are two main rules for constructing a hierarchical model. First, where possible, the performance parameters included in the model should be mechanical quantities, and second, each of the performance parameters should be completely determined by those performance parameters that appear directly below it (Hay & Reid, 1988). By employing this systematic approach to model development, no performance parameter that influences the outcome is overlooked and no performance parameter is included more than once.

Once a hierarchical model has been constructed, the most important performance parameters and their relative contribution to successful motor performance need to be empirically verified. Typically, two basic experimental research designs are used for verification—the correlation approach and the contrast approach (Hay, Vaughan, & Woodworth, 1981). In the correlation approach, relationships between the performance criterion and the underlying performance parameters for a single homogenous group are formally examined using multiple or partial correlation statistics. Conversely, in the contrast approach, differences in the mean values of key performance parameters for two or more heterogeneous groups are formally examined using mean difference statistics. An advantage of having a rigorously developed hierarchical model at this stage of an investigation is that performance parameters can be selected

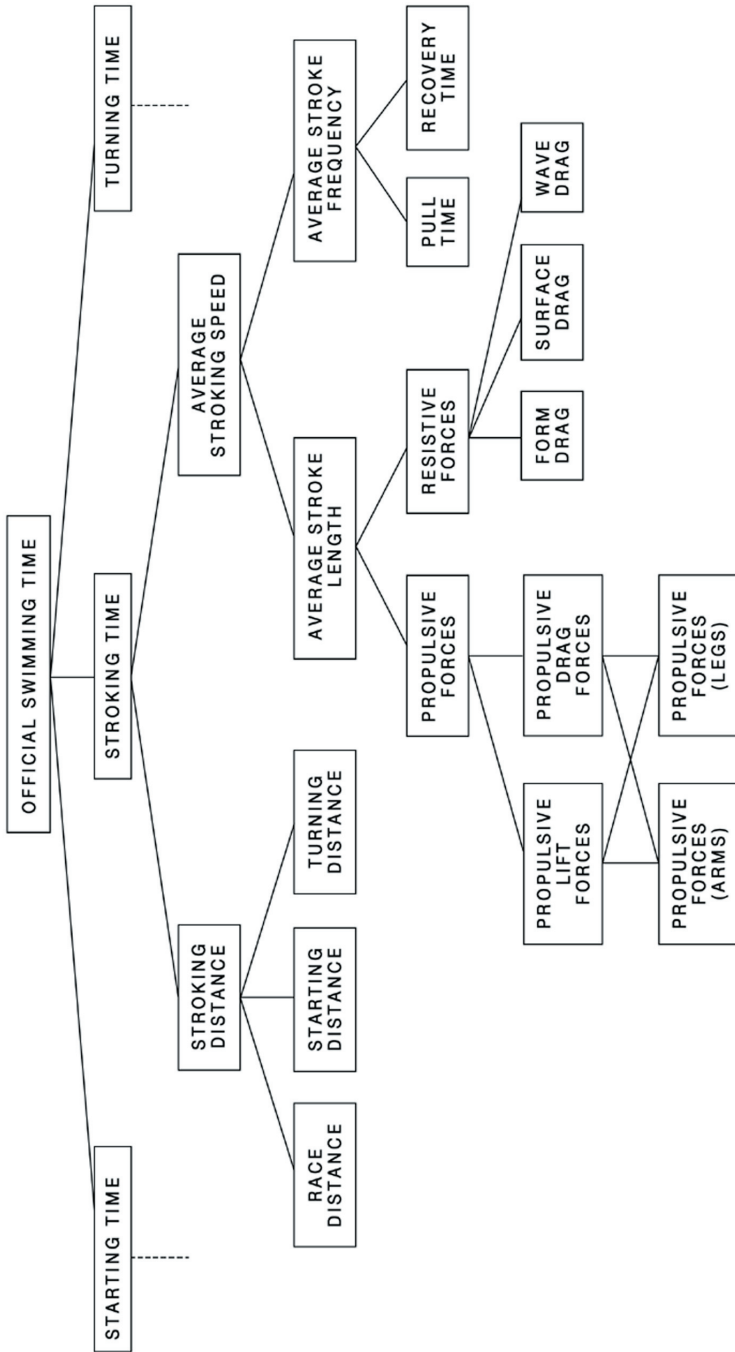


FIGURE 3.1 A hierarchical model outlining the factors that underpin performance in swimming.

Adapted from Hay, 1993.

and justified on the basis of a sound theoretical rationale. Using the hierarchical modeling approach can therefore be considered superior to the arbitrary shotgun approach in which performance parameters tend to be randomly selected, as the model helps ensure that all the truly important variables are included and all the trivial ones are omitted.

Although hierarchical models have been used predominantly in performance-related research, they have also been adapted for use in injury-related research to identify possible injury mechanisms (e.g., Dixon & Kerwin, 1998). More specifically, hierarchical models can be useful for determining the characteristics of technique that might cause excessive loading or stress and lead to injury by exceeding the critical stress limits of the biomaterials (Nigg, 1985; Whiting & Zernicke, 1998; Zernicke & Whiting, 2000). As in performance-related research, once potentially harmful mechanical factors are identified, the relationships between kinematic or kinetic variables and injury can be formally evaluated using correlation statistics. This approach, which was termed the *empirical approach* by Nigg and Bobbert (1990), ideally incorporates a prospective research design in which individuals are monitored over time and analyzed on a post hoc basis when identifying the source of the injury, as it is inherently difficult to ascertain cause and effect with retrospective designs. Moreover, prospective designs provide the scope to subsequently manipulate population samples and implement alternative statistical analyses that might be more effective at identifying 'offending' characteristics of movement (see Foster, John, Elliott, Ackland, & Fitch, 1989; Elliott, Hardcastle, Burnett, & Foster, 1992).

Interpretations of Movement Variability

In the past, sport biomechanists have rarely considered movement variability to be an important topic worthy of research attention in its own right. There appears to be a number of interrelated reasons why researchers have ignored this aspect of human motor performance. First, biomechanical analyses examining the kinematics of human motion have typically been inhibited by the design of equipment for motion analysis and the inefficiency of techniques for data reduction. A main problem is the laborious nature of manual coordinate digitizing, which has typically restricted kinematic analyses to a single performance trial and has, therefore, precluded analysis of any trial-to-trial variability. Second, an implicit assumption held by many sport biomechanists is that human motor performance is characterized by invariance in the motor system (Schmidt, 1985) and, therefore, trial-to-trial variability has typically been deemed to have negligible practical significance. This assumption appears to have been perpetuated by the concept of motor programming that has dominated the movement sciences for the past three decades (e.g., Keele, 1968; Schmidt, 1982). On the premise that patterns of movement are highly consistent over repeated trials, the analysis of a single performance trial has been justified on the grounds that it represents a performer's normal technique. Third, the fre-

quent use of hierarchical models has encouraged sport biomechanists to adopt a reductionist approach in searching for performance parameters that contribute most to the performance criterion. However, these performance parameters do not provide any information about the underlying patterns of coordination that generate these performance parameters (see figure 3.1). In principle, a multitude of different movement patterns could be used to produce the same set of performance parameter values. The emphasis is very much outcome-oriented rather than process-oriented, and in this respect, shares many of the problems that have dogged traditional research in motor behavior. Fourth, sport biomechanists often make the significant assumption that people share a common optimal pattern of movement. In other words, they believe there is a single most efficient and effective way of performing a movement in the majority of the population (Brisson & Alain, 1996). On the basis that highly skilled performers are likely to have 'more optimal' techniques than their lesser skilled counterparts, pooled group data are typically analyzed using inferential statistics to establish 'normative' values for specific performance parameters. Any group-based differences can then be used to develop generalizable laws of action that may be used to characterize a hypothetical ideal technique or motor template. However, when pooling group data, any performer-to-performer variability tends to get masked as scientists focus on the 'big picture' to the detriment of understanding the emergence of individualized movement solutions. Literally, biomechanists cannot see the 'trees for the forest'. Fifth, any observed moment-to-moment variability in kinematic time series data has invariably been treated as random measurement errors and has either been disregarded or removed using recognized data filtering and smoothing techniques (for example, see Wood, 1982). In chapter 1, Newell and colleagues discuss the inadequacies of treating all observed movement variability as random variability.

Dynamic Systems Theory Applied to Sport Biomechanics

So far in this chapter, we have critically analyzed the philosophical and theoretical paradigms used in applied research in sport biomechanics. It is clear from the literature that if significant progress is to be made in both performance-related and injury-related sport biomechanics, more complex research questions based on the sound theoretical rationale of dynamic systems need to be formulated. In turn, these questions require more innovative research designs and methods of analysis (see Stergiou, 2003 for a review). Wherever possible, a combination of group and single-individual designs should be incorporated so that both intra- and inter-individual differences can be analyzed. Moreover, greater emphasis should be directed towards analyzing actual patterns of movement, instead of discrete kinematic measurements, as they provide a window into the underlying dynamics of the sensorimotor system. The use of more innovative

research designs and methods of analysis will also enable sport biomechanists to more thoroughly examine the role of movement variability in human motor performance. In the following sections, we discuss the potential applications of dynamic systems theory to performance-related research in sport biomechanics, focusing on movement models of terrestrial and aquatic gait, and we examine how this new view of movement variability could be, and has been, used to enhance injury-related research in sport biomechanics.

Performance-Related Research in Sport Biomechanics

Perhaps the most pertinent example of how biomechanics has improved sport performance is the work of Counsilman (1968, 1969, 1971), Brown (Brown & Counsilman, 1971), Schleihauf (1974, 1979), and others (Hay, Liu, & Andrews, 1993; Liu, Hay, & Andrews, 1993) on the generation of propulsive forces in freestyle swimming. Before this research, the general consensus among swimming practitioners was that propulsive forces were generated predominantly by hydrodynamic drag created by moving the hand directly backwards during the pull phase of the swimming stroke (Cureton, 1930; Kiphut, 1942; Armbruster & Morehouse, 1950). However, using underwater photography, Brown and Counsilman (1971) observed that world-class freestyle swimmers use other techniques involving complex curvilinear hand paths. This observation led the authors to suggest that propulsive forces in freestyle swimming are generated predominantly by hydrodynamic lift created by medial and lateral sculling movements of the hand during the pull phase of the swimming stroke. Further research by Schleihauf (1979) and Schleihauf, Gray, and De Rose (1983) has since provided empirical evidence that propulsive forces in freestyle swimming are generated by both hydrodynamic lift and drag.

Although more recent computer simulation and experimental research by Hay et al. (1993) and Liu et al. (1993) has shown that much of the lateral movement of the hand during freestyle swimming is caused by body roll² rather than by horizontal movements of the arms relative to the swimmer's body, there can be no mistaking the contribution of the original work by Counsilman and others to the understanding of how propulsive forces are generated in freestyle swimming. Despite recent suggestions that the original work of Counsilman and others was, in fact, flawed (see Sanders, 1998), this series of investigations has not only provided a solid foundation for scientific endeavour in this area of study, but it has also profoundly influenced the teaching and coaching of freestyle swimming techniques over the past three decades. Indeed, their contribution has been widely acknowledged as one of the most significant made by sport biomechanists to the enhancement of knowledge and performance of sports techniques since biomechanics emerged as an academic discipline in the 1960s (Hay, 1983; Bartlett, 1997).

²Body roll can be defined as the angular displacement along the longitudinal axis of the swimmer's body.

Although maximizing propulsive forces in freestyle swimming is an important factor in proficient performance, it is equally important to minimize resistive drag forces, which act on the swimmer to inhibit forward motion (see figure 3.1). As with many other sports techniques, an 'optimal' freestyle swimming technique can be described as one that is both highly efficient and effective. In general, efficiency refers to the relationship between energy input and energy output in the athlete-environment system. To optimize efficiency in swimming, it is necessary for a swimmer to maximize the utilization of biochemical energy generated by the anaerobic and aerobic metabolic energy systems (energy input) by using techniques that most effectively generate mechanical energy (energy output) to maximize propulsive forces. To optimize effectiveness, however, it is necessary for these techniques to maximize propulsive forces whilst minimizing resistive drag forces, which are influenced by, amongst other factors, the size and shape of the swimmer, and swimming speed. As these resistive drag forces are constantly fluctuating, an effective freestyle swimming technique must be sufficiently flexible and adaptable to enable emerging patterns of coordination to be modified according to these and other constraints impinging on the swimmer.

In this section, to exemplify the functional role of movement variability, we examine the different strategies that might be used by swimmers to maintain optimum efficiency and effectiveness in relation to key performance constraints. We specifically focus on the effect of swimming speed on emerging patterns of coordination. It is important to note, however, that although swimming speed is likely to be one of the most important constraints acting on the swimmer, it is the interaction of all the different types of organismic, environmental and task constraints that ultimately determines the morphology of the ensuing patterns of coordination (Newell, 1986; Newell, van Emmerik and McDonald, 1989). From the perspective of dynamic systems theory, any variability in movement patterns could be interpreted as reflecting the conscious or unconscious attempt to satisfy, in the best way possible, the unique confluence of constraints impinging on the swimmer—a process referred to as self-organizing optimality by Newell (1986).

Although success in most sports activities is governed by the efficiency and effectiveness of the techniques used by the individuals participating in those activities, swimming is unique in that swimmers during aquatic gait must satisfy the task constraint of moving their bodies through the medium of water while virtually all other athletes move through air. Owing to the increased density of water, which is approximately 800 times greater than air, the magnitude of resistive drag forces is increased dramatically. Consequently, swimming has been calculated to be less than 9% mechanically efficient (Toussaint, Knops, DeGroot & Hollander, 1990), whereas other forms of terrestrial gait, such as walking and running, have been estimated to be between 20% and 80% mechanically efficient depending on the method used to calculate mechanical efficiency (see Williams, 1985).

A further important task constraint influencing the magnitude of resistive drag forces in swimming is the relative speed of the swimmer to the oncoming flow of water. Indeed, according to the equations used to calculate resistive drag, there is a quadratic relationship between drag and swimming speed. One of the artifacts of increasing swimming speed is that the point of boundary layer³ separation moves further upstream towards the head of the swimmer, leading to the generation of high-energy eddies or vortices and a large low-pressure area of water further downstream from the swimmer. As there is also a concurrent high-pressure build-up of water in front of the swimmer, a large pressure gradient is created, which significantly increases the magnitude of resistive drag forces experienced by the swimmer. To maintain optimum efficiency and effectiveness under these changeable environmental constraints, swimmers need to be able to readily adjust their swimming techniques and the patterns of propulsive forces produced within the task constraints imposed by the rules governing the specific swimming stroke.

As we briefly mentioned at the beginning of this section, another important characteristic of an effective freestyle swimming technique is body roll because it facilitates lateral movements of the arm during the pull phase of the swimming stroke, enabling the hand to interact with 'new' water or water that has not already had kinetic energy imparted to it by the swimmer's hand (Hay et al., 1993). With the hand pulling against stationary water, 'slippage' is reduced and larger reaction forces can be generated. One of the effects of increasing swimming speed, however, is that body roll invariably decreases, which causes lateral movements of the arm to decrease and the hand path to become more linear during the pull phase (Hay et al., 1993). As the hand is pushing against water that has already had kinetic energy imparted to it, 'slippage' is increased and smaller reaction forces are generated, which consequently causes a change in the pressure distribution exerted by the water on the swimmer's hand. On the basis of this change in the water's 'feel'—acting as an important informational constraint on performance—the patterns of movement produced by the swimmer's arm and the orientation of the hand during the pull phase need to be modified to increase the propulsive forces generated by the hand.

The preceding analysis of aquatic gait exemplifies how interacting organismic, environmental and task constraints shape the relatively unique patterns of coordination that emerge during performance for individual swimmers. Despite the clear need to understand how patterns of coordination are modified during performance, this aspect of performance has rarely been examined in the literature. The main reason for the lack of research attention appears to originate from the fact that most scientific investigations (e.g., Craig and Pen-

³The boundary layer is the layer of water across which the relative velocity between the swimmer and the water adjusts from zero at the surface of the swimmer's body to the free stream velocity, which, in the present example, is the velocity of the swimmer.

dergast, 1979; Hay & Guimaraes, 1983; Grimston and Hay, 1986; Keskinen, Tilli and Komi, 1989; Arellano and Pardillo, 1992; McArdle and Reilly, 1992; Keskinen, 1993) have tended to adopt a reductionist approach and examine those descriptive stroke characteristics that are more readily observable from the pool deck such as swimming speed, stroke length and stroke frequency, rather than the actual patterns of coordination that produce them. Moreover, the selection of these stroke characteristics has been justified on the basis that they represent important performance parameters, which are strongly related to the performance criterion (see figure 3.1). Although the vast majority of studies have focused on stroke characteristics, there have been a few studies that have examined, with varying degrees of success, patterns of coordination in swimming. A major limitation of these studies, however, was that they tended to analyze either spatial (Ringer and Adrian, 1969) or temporal characteristics separately and not together (Vaday and Nemessuri, 1971; Chollet, Chabies and Chatard, 2000). Clearly, future empirical studies on this aspect of swimming performance need to examine the space-time characteristics of patterns of movement using analytical techniques such as those outlined in chapter 7 by Button, Davids & Schöllhorn, and chapter 9 by Wheat & Glazier.

How swimmers actually adjust their coordination patterns as swimming speed increases is, therefore, of great importance to practitioners and sport scientists. Small-scale adjustments to the orientation of the hand, based on changes in the 'feel' of the water, may be made prospectively in skilled swimmers because of the tight coupling between the perception and movement sub-systems. However, large-scale changes in whole body patterns of coordination may be necessary to maintain optimal efficiency and effectiveness, particularly with the concurrent increase in resistive drag forces experienced by the swimmer. It is feasible that a non-equilibrium phase transition or bifurcation, characterized by a shift from one state of coordination to another by the swimmer, may occur (e.g., Kelso, Southard and Goodman, 1979; Kelso, Holt, Rubin and Kugler, 1981; Beuter, Flashner and Arabyan, 1986; Kelso, Scholz and Schöner, 1986; Scholz and Kelso, 1989; Kelso and Jeka, 1992). As we discussed earlier, bifurcations are characterized by increased variability of a relevant order parameter (e.g., relative phase) and are brought about by a systematic change in a relevant control parameter (e.g., swimming speed). These bifurcations have been observed in many different types of motion such as finger wagging (e.g., Kelso, 1984), human gait (e.g., Diedrich and Warren, 1995), equine gait (e.g., Hoyt and Taylor, 1981) and the swimming motion of marine animals (e.g., Alexander, 1989; Drucker, 1996) and have been suggested to occur for a variety of reasons, including optimizing mechanical efficiency (Grillner, Halbertsma, Nilsson and Thorsyensson, 1979; Hoyt and Taylor, 1981; Alexander, 1984, 1989; Taylor, 1985) and decreasing muscular contraction velocity and the associated muscular and joint forces (Hreljac, 1995). Despite these different explanations, and the greatly varied physical and physiological make-up of humans, the speed at which adults change from a walking gait to

a running gait has been consistently shown to be approximately 2.5 m/s (Alexander, 1984). Owing to the apparent ubiquity of phase transitions in human and animal movement, it is likely that such a phase transition would be evident during aquatic gait among swimmers of a similar size and ability.

A possible factor influencing the speed at which phase transitions might occur is the training methods used by many of today's leading swimmers, which typically consist of large volumes of relatively slow swimming (approximately 1.2 m/s). According to the principle of specificity of training, combined with the empirical findings of Zanone and Kelso (1992), only the patterns of coordination, or attractor states, used by the swimmer at these lower speeds are likely to be developed. However, since competition swimming speeds are typically much higher (approximately 2 m/s) than the typical training pace, swimmers are likely to adopt a different pattern of coordination when swimming at these higher speeds. Owing to their lack of training at these higher speeds, swimmers are unlikely to maintain stability of alternative patterns of coordination and hence their speed would decrease after a relatively short period of time. At that point, swimmers are likely to transit back to the more stable patterns of coordination established during training.

With the theoretical possibility of the existence of phase transitions or a new attractor states emerging during swimming, and with the lack of previous research, it is unclear whether swimmers are training under appropriate task constraints by swimming at speeds lower than those habitually used in competition. The principle of specificity of training dictates that task constraints between training and competition conditions (e.g., swimming speed) should remain consistent to enhance the stability of coordination patterns used at high swimming speeds. However, sport scientists and practitioners should remain tolerant of functional variability shown by swimmers in the emergent adaptations to basic coordination of patterns of aquatic gait owing to the interaction of organismic, environmental and task constraints. Clearly, further investigations based on dynamic systems theory are necessary to establish whether separate walking- and running-type strokes exist and, if so, how specific current training and conditioning programs of top freestyle swimmers are in terms of developing stable running-type strokes.

Injury-Related Research in Sport Biomechanics

Recently, a dynamic systems approach has been used in injury-related research in sport biomechanics to examine lower-extremity running injuries (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit, Hamill, & van Emmerik, 1999; Heiderscheit, 2000a, 2000b; Heiderscheit, Hamill, & van Emmerik, 2002). A criticism of previous research on lower-extremity running injuries is that kinematic analyses have almost exclusively focused on time-discrete variables obtained from isolated joints or segments, such as maximum rear-foot pronation, maximum velocity of rearfoot pronation, and maximum tibial internal rotation (e.g., Clarke, Frederick, & Hamill, 1984; Messier & Pittala,

1988; Duffey, Martin, Cannon, Craven, & Messier, 2000). A major problem with this approach is that it fails to take into account the relative motions of various lower-extremity segments or joints, such as the subtalar and knee joints, which have frequently been implicated in the etiology of overuse injuries to the knee (Bates, James, & Osternig, 1978; Lafortune, Cavanagh, Sommer, & Kalenak, 1994; McClay & Manal, 1997; Stergiou & Bates, 1997; Hintermann & Nigg, 1998; Nawoczenski, Saltzman, & Cook, 1998; Stergiou, Bates, & James, 1999). A dynamic systems approach overcomes this problem, as it focuses on the coordination or coupling among segments or joints (Hamill et al., 1999). In this section, we briefly review the research by Hamill, Heiderscheit, and colleagues on lower-extremity running injuries, highlighting the utility of this relatively new approach and specifically focusing on variability in coordination and its relationship to injury.

Previously, the quadriceps angle (Q-angle) has been proposed as an important factor in the etiology of patellofemoral pain⁴ (Subotnick, 1975; Cox, 1985; Messier & Pittala, 1988; Messier, Davis, Curl, Lowery, & Pack, 1991). The Q-angle is formed by the intersection of a line projected through the center of the patella from the tibial tuberosity and a line connecting the center of the patella to the anterior superior iliac spine of the pelvis (see figure 3.2). Subotnick (1975) hypothesized that a large Q-angle may cause excessive foot pronation or rearfoot eversion, increasing tibial internal rotation and altering tracking of the patella if accompanied by external femoral rotation. Furthermore, Cox (1985) suggested that altering the tracking of the patella changes the contact regions and pressure distributions in the patellofemoral joint, thus predisposing patellofemoral pain.

In their first reported study, Hamill et al. (1999) examined the influence of the Q-angle on the coordination and variability in the coordination of lower-extremity body segments during over-ground running. Healthy individuals with Q-angles greater than 15° were compared to healthy individuals with Q-angles less than 15°, as it has been suggested that the former might be more susceptible to lower-extremity injury (Messier et al., 1991). The assigned task was to run repeatedly over a force platform (used to identify initial foot contact) at speeds between 3.60 and 3.83 m/s—the range typically used by most non-competitive runners (Cavanagh, 1987). Standard three-dimensional filming and reconstruction techniques were used to obtain kinematic data describing the space-time characteristics of lower-extremity body segments. Coordination among lower extremity body segments was assessed using the continuous relative phase (CRP) technique (see chapter 9 by Wheat & Glazier). CRP profiles for the following couplings were calculated: thigh flexion and extension and tibial rotation, thigh abduction and adduction and tibial rotation, and tibial rotation and foot eversion and inversion. Each of these CRP profiles was interpolated and normalized to 100 data points and an ensemble average CRP profile for

⁴ Patellofemoral pain is a term used to describe generalized pain in the anterior knee (Winter and Bishop, 1992).

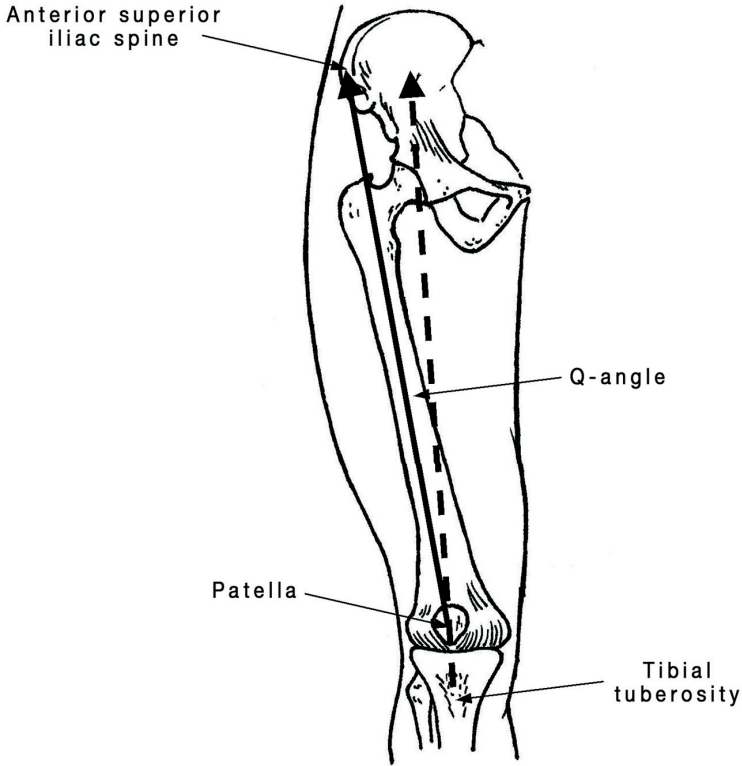


FIGURE 3.2 The quadriceps angle (Q-angle).

each coupling was constructed from ten trials performed by each individual. To quantify variability in coordination, the CRP standard deviation (CRP_{SD}) was calculated at each of the 100 data points. In addition to calculating the average CRP and average CRP_{SD} over the entire stance phase, average CRP and average CRP_{SD} over the following intervals of the stance phase—determined by key events in rearfoot inversion-eversion—were calculated: from initial foot contact to the neutral position, from the neutral position to maximum eversion, from maximum eversion to the neutral position, and from the neutral position to toe-off.

The main finding of this study was that despite the differences in Q-angle, there were no statistically significant differences between the two groups for all three couplings during the entire stance phase, both in terms of the average CRP and the average CRP_{SD} . However, among the four intervals of the stance phase, there were systematic differences in the average CRP and average CRP_{SD} for all three couplings. Generally, all three couplings were out of phase between initial foot contact and the neutral position but, as the stance phase progressed,

the tibial rotation and foot eversion and inversion coupling became increasingly in phase, and the thigh flexion and extension and tibial rotation coupling and, more particularly, the thigh abduction and adduction and tibial rotation coupling, became increasingly out of phase. Perhaps more importantly, the average CRP_{SD} of all three couplings during the period between initial foot contact and the neutral position was considerably greater than the average CRP_{SD} during any other interval of the stance phase.

In a follow-up study, Heiderscheit et al. (1999) used a similar research design and method to examine the influence of the Q-angle on variability in coordination. Again, no statistically significant differences in average CRP_{SD} were found between the low Q-angle group and the high Q-angle group for all three couplings over the entire stance phase. However, among the four intervals of the stance phase, statistically significant differences in average CRP_{SD} were found for all three couplings. During the period between initial foot contact and the neutral position, both the thigh flexion and extension and tibial rotation and the thigh abduction and adduction and tibial rotation couplings displayed significantly greater average CRP_{SD} than during any other interval of the stance phase. Moreover, the average CRP_{SD} for the tibial rotation and foot eversion and inversion coupling during the period between initial foot contact to the neutral position was significantly greater than during the period between the neutral position to maximum eversion. Overall, the average CRP_{SD} for all couplings was greatest during the period between initial foot contact to the neutral position, and it generally decreased throughout the remainder of the stance phase.

From the results of these two studies, it appears that variability in coordination during the period between initial foot contact and the neutral position of the stance phase is an important feature of normal, healthy running. Holt, Jeng, Ratcliffe, & Hamill (1995) reported similar findings for walking, which led them to suggest that variability in coordination during this period of the gait cycle could have important implications for injury prevention and performance enhancement. First, by constantly varying the point of force application, different anatomical surfaces are exposed over repeated trials, thereby preventing the overloading of the same anatomical surface and limiting overuse injuries (see Nigg, 1985). Second, variability in coordination during this interval could provide the flexibility necessary to adapt to environmental perturbations such as uneven terrain or irregular surfaces and thus reduce the risk of injury through falling.

In their second reported study, Hamill et al. (1999) examined the influence of patellofemoral pain on the coordination and variability in the coordination of lower-extremity body segments during motorized treadmill running. In this study, individuals with patellofemoral pain were compared to those with no history of patellofemoral pain. As in their first study, Hamill et al. (1999) used standard three-dimensional filming and reconstruction techniques to obtain kinematic data describing the space-time characteristics of lower-extremity body

segments. However, in this study, subjects were recorded throughout the entire stride cycle and at three different running speeds (2.5, 3.0, and 3.5 m/s). CRP and CRP_{sd} for the three body segment couplings described in the first study were calculated, and an additional femoral rotation and tibial rotation coupling was also included to examine the possible influence of antagonistic rotations of these segments on patellofemoral pain. In addition to calculating average CRP and average CRP_{sd} over the swing phase, the stance phase, and the entire stride cycle of each trial, average CRP and average CRP_{sd} were calculated for each of the four intervals of the stance phase we previously described for the first study by Hamill et al. (1999).

As the results obtained from the three different running speeds were similar, only data for the trials ran at 2.5 m/s were reported. Although slight differences between the two groups were found in the average CRP for all four couplings throughout the entire stride cycle, the greatest differences were apparent during the interval between neutral position and maximum eversion and the interval between maximum eversion and the neutral position, in which the individuals with patellofemoral pain were more in phase for the thigh abduction and adduction and tibial rotation coupling. However, the main finding of this study was that the average CRP_{sd} of each of the four couplings was consistently less in the individuals with patellofemoral pain than in those with no history of patellofemoral pain, particularly during the transition from stance to swing, throughout the swing phase, and during the transition from swing to stance. This finding appears to contradict traditional clinical and biomechanical wisdom, which generally assumes that the amount of variability directly relates to the degree of pathology. Although Hamill et al. (1999) suggested that this lack of variability could relate to a loss of complexity through the development of patellofemoral pain, it is difficult to prove cause and effect with this type of retrospective research design. In other words, it is unclear whether the lack of variability is the cause or the effect of patellofemoral pain. As we discussed earlier, a prospective design (Nigg and Bobbert, 1990) could help overcome this problem. Despite the design limitation, however, subsequent research by Heiderscheit (2000a) appears to empirically support the original hypothesis postulated by Hamill et al. (1999) regarding the relationship between variability in coordination and patellofemoral pain. By monitoring changes in variability in coordination during treatment, Heiderscheit (2000a) found that the reduction of patellofemoral pain coincided with an increase in variability. These findings provide some support for the notion that patellofemoral pain may be the cause rather than the effect of reduced variability.

In another study, Heiderscheit et al. (2002) examined the influence of patellofemoral pain on the variability of joint coordination and of stride characteristics (e.g., stride duration and stride length). As we just discussed, increased variability of body segment coordination has been reported in healthy individuals as compared to individuals with patellofemoral pain (Hamill et al.,

1999). However, no information is available regarding the influence of patellofemoral pain on the variability of stride characteristics. Previously, it has been shown that variability of stride characteristics increase the risk of falling in elderly individuals (Gabell & Nayak, 1984; Nakamura, Meguro, & Sasaki, 1996; Hausdorff, Edelberg, Mitchell, Goldberger, & Wei, 1997) and that it is related to neuromuscular diseases such as Huntington's disease and Parkinson's disease (Hausdorff, Cudkowicz, Firtion, Wei, & Goldberger, 1998). Therefore, whereas variability of joint coordination might be considered functional because it appears to protect against overuse injuries and aid adaptation to environmental perturbations, variability of stride characteristics might be considered dysfunctional, as it appears to be associated with postural instability and an increased likelihood of injury through falling.

In the study by Heiderscheit et al. (2002), the variability of stride characteristics was compared to the variability of joint coordination in individuals with symptoms of unilateral patellofemoral pain and nonimpaired individuals. The task of each individual was to run on a motorized treadmill at two different speeds—a preferred running speed and a fixed running speed. Each individual was able to select a preferred running speed between 0.5 and 8.0 m/s by manually adjusting the speed of the motorized treadmill. A fixed running speed of 2.68 m/s for all individuals was selected to avoid coinciding with the transition between walking and running or between running and walking (which occurs between 1.8 and 2.2 m/s). A system for automated motion analysis was used to capture and reconstruct 15 consecutive strides at both the preferred and fixed running speeds for each of the individuals. Bilateral three-dimensional kinematic data describing the space-time characteristics of lower-extremity segments were generated and relative motion plots were constructed for the following joint couplings: femoral rotation and tibial rotation, hip flexion and knee flexion, knee rotation and ankle inversion, knee flexion and ankle inversion, and knee flexion and ankle dorsiflexion. As the data were predominantly nonsinusoidal, a modified vector coding technique (Sparrow, Donovan, van Emmerik, & Barry, 1987) was used to quantify joint coordination (see chapter 9 by Wheat & Glazier). As in the studies we previously described, the stride cycle was divided into five intervals, with each interval containing a functional event (i.e., midstance, toe-off, swing acceleration, swing deceleration, and heel strike). The variability of joint coordination was quantified by calculating the average standard deviation within each of these periods as well as over the entire stride cycle. Kinematic data describing stride length and stride duration were also obtained for the 15 strides at each running speed. The mean and standard deviation of each of these parameters were then used to calculate the coefficient of variation (CV), which was used to quantify the variability of stride characteristics for each of the individuals.

Several important findings emerged from this study. First, the average CV for stride length obtained from the individuals with unilateral patellofemoral pain was significantly greater than that obtained for nonimpaired individuals

at the preferred running speed. This finding appears to concur with previous research reporting an increased variability of stride length in individuals at risk of falling (Gabell et al., 1996; Hausdorff et al., 1997) and in individuals with various neurological diseases (Hausdorff et al., 1998). However, as there was no significant difference in the average CV for stride length between the groups at the fixed running speed, Heiderscheit et al. (2002) remained skeptical about the generalizability of these results. Second, no significant differences in variability of joint coordination existed between the injured and noninjured limbs of the individuals with patellofemoral pain when variability was analyzed over the entire stride cycle. Moreover, no significant difference in variability existed between the individuals with unilateral patellofemoral pain and the nonimpaired individuals when variability was analyzed over the entire stride cycle. However, in the coupling between thigh rotation and leg rotation, a significant difference in variability of joint coordination existed between the injured and noninjured limbs of the individuals with patellofemoral pain among the five intervals of the stride cycle. Although Heiderscheit et al. (2002) suggested that this difference could simply be an error in measurement, the decreased variability in the injured limb during the interval containing heel strike at the preferred running speed appears to concur with previous research by Hamill et al. (1999). Heiderscheit et al. (2002) found that the injured limbs of individuals with patellofemoral pain exhibited less variability than either limb of the nonimpaired individuals, but neither limb of the nonimpaired individuals exhibited as much variability in coordination as the noninjured limbs of the individuals with patellofemoral pain. The concurrent increase in the variability of the noninjured limb with the decrease in the variability of the injured limb implies a compensatory mechanism. Similar findings have been reported in children with spastic hemiplegic cerebral palsy (see Jeng, Holt, Fetters, & Certo, 1996).

Despite the limitations of the studies outlined in this section, it appears that a dynamic systems approach could greatly assist in the detection, treatment, and rehabilitation of running injuries (see also chapter 8 by Hamill, Haddad, van Emmerik, Heiderscheit & Li). For example, by examining the variability in coordination of lower-extremity body segments, scientists in sport biomechanics and clinicians might be able to detect the gradual deterioration of sensorimotor functioning and predict the onset of overuse injuries, as variability in coordination appears to inversely relate to the degree of pathology. Likewise, by examining variability in coordination during treatment and rehabilitation, scientists in sport biomechanics and clinicians can monitor the effectiveness of treatment modalities and estimate the extent of recovery, which could help prevent a premature return to physical activity and avoid compounding the original injury. Furthermore, by examining the coordination between lower-extremity body segments it may be possible to ascertain the cause of injury. Although Hamill et al. (1999) failed to identify any significant differences in the coordination of lower-extremity components between injured and noninjured individuals, it is hard to dispute the plethora of anecdotal evidence that implicates a disruption

to the relative motions of the segments comprising the knee joint as a major factor in the etiology of overuse injuries. Only further research using a dynamic systems approach can verify the accuracy of these claims.

Clearly, the emphasis on the coordination and the variability in coordination of body segments and joints has already provided more useful information about lower-extremity running injuries than conventional research designs in sport biomechanics, which have generally failed to provide empirical evidence relating the mechanics of the lower-extremity body segments to knee injury (McClay, 2000; Deleo, Dierks, Ferber & Davis, 2004). The emergence of a dynamic systems approach appears to be particularly timely in this respect, as an increasing number of individuals from the medical profession have begun to question whether biomechanics has made a meaningful contribution to the diagnosis, treatment, and prevention of running injuries. From the evidence presented in this section, it appears that adopting a dynamic systems approach and using variability in coordination as a clinical measurement (see Heiderscheit, 2000b) may enhance the richness and improve the productivity of injury-related research in sport biomechanics. Although we have focused predominantly on running injuries in the lower extremity, it is likely that this relatively new approach is equally applicable to the general study of orthopedic injuries.

Concluding Remarks

In this chapter, we have used examples from the literature to demonstrate the utility of dynamic systems theory in performance-related and injury-related research in sport biomechanics. We have shown that dynamic systems theory not only provides the scope for alternative research designs, but also provides a scientifically rigorous theoretical rationale that some individuals from other disciplines of sport science might argue, albeit incorrectly, does not presently exist in applied research in sport biomechanics. Although this relatively new approach has yet to become routine in sport biomechanics, some of the examples outlined in this chapter suggest that it could provide more important information for performance enhancement and injury prevention than other research designs currently being used. Importantly, dynamic systems theory provides the scope, rationale, and methods to examine more thoroughly the functional role of movement variability, which has, to date, been rarely investigated by sport biomechanists.

