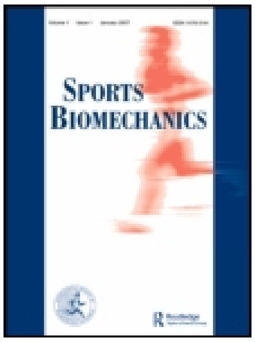

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Is movement variability important for sports biomechanists?

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Abstract
This paper overviews the importance for sports biomechanics of movement variability, which has been studied for some time by cognitive and ecological motor skills specialists but, until quite recently, had somewhat been overlooked by sports biomechanists. The paper considers biomechanics research reporting inter- and intra-individual movement variability in javelin and discus throwing, basketball shooting, and locomotion. The overview does not claim to be comprehensive and we exclude such issues as the theoretical background to movement and coordination variability and their measurement. We overview evidence, both theoretical and empirical, of inter-individual movement variability in seeking to achieve the same task goal, in contrast to the concept of "optimal" movement patterns. Furthermore, even elite athletes cannot reproduce identical movement patterns after many years of training, contradicting the ideas of motor invariance and "representative" trials. We contend that movement variability, far from being solely due to neuromuscular system or measurement "noise" – as sports biomechanists may have previously supposed – is, or could be, functional. Such functionality could allow environmental adaptations, reduce injury risk, and facilitate changes in coordination patterns. We conclude by recommending that sports biomechanists should focus more of their research on movement variability and on important related topics, such as control and coordination of movement, and implications for practice and skill learning.

Keywords: *Basketball shooting, constraints, coordination, javelin throwing, movement variability, running*

Introduction

Until the last decade or so, sports biomechanists tended to assume that intra-individual variability in movement patterns was "noise", not an important issue in research design or measurement. One reason for this has been researchers' implicit assumption that movement patterns for skilled performers are invariant – clearly, in the light of recent research, a false assumption.

In this paper, we overview sports biomechanics research into variability in movement and coordination patterns, focused around throwing skills in track and field athletics and basketball, and locomotion. We start with some research by Bartlett and his colleagues into javelin throwing, which reported variability – even though that was not necessarily the main focus – between elite throwers and within throwers, and from computer simulations that

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seemed to predict movement variability. We then move on to research into variability in basketball shooting and locomotion. We contend that movement and coordination variability are, or could be, functional. Such functionality could allow environmental adaptations, reduce injury risk, and facilitate changes in coordination patterns. We conclude by outlining what we believe movement variability means for sports biomechanists and for practitioners. This paper does not cover in depth the theoretical background to movement variability, which would be inappropriate for this journal, although we introduce some important theoretical ideas, particularly in the section on locomotion (see also Davids, Araújo, Glazier, and Bartlett, 2003; Davids, Bennett, and Newell, 2006; Glazier, Wheat, Bartlett, and Pease, 2006). Nor is the focus of this review on how movement coordination and variability are measured; these topics have been extensively and recently addressed elsewhere (see, for example, reviews by Hamill, Haddad, and McDermott, 2000; James, 2004; Wheat and Glazier, 2006).

Variability in javelin (and discus) throwing

Morriss, Bartlett, and Fowler (1997) reported the results of a study of the men's javelin final in the 1995 World Athletics Championships, with a focus on arm contributions to release speed. The very large shoulder angular velocity for the silver medallist suggested a reliance on shoulder horizontal flexion and extension to accelerate the javelin, which would suit his linear throwing style. In contrast, the gold medallist used medial rotation of the shoulder as a major method of accelerating the javelin. This movement, combined with an elbow extension angular velocity that was at least 18% larger than for any other of the 12 finalists, was an important part of the reason he was able to achieve the greatest release speed. The other finalists used various combinations of these three arm movements to generate release speed. Such differences between throwers hardly support the idea of a common optimal motor pattern or technique, and question the approach of trying to copy the most successful performers. These differences may be the result of the individual-specific self-organization process (see Clark, 1995), such that performers find unique solutions to a task, although some of these solutions may be sub-optimal.

Morriss et al. (1997) speculated that these differences in the movements of the upper arm and forearm between throwers have important implications for their physical training. The training exercises performed by each thrower should be done in a way that replicates their individual movement patterns, such that the gold medallist, for example, when throwing a ball should emphasize shoulder medial rotation and elbow extension to ensure movement specificity (Enoka, 1994).

Further evidence against the idea of a common optimal technique has been provided, for example, from self-organizing Kohonen maps for javelin throwing by Schöllhorn and Bauer (1998) and for discus throwing by Bauer and Schöllhorn (1997). Kohonen maps are artificial neural networks that can be used to reduce complexity by, for example, mapping multiple time-series data on to simple two-dimensional outputs. Although this approach is still novel in sports biomechanics, the results of these theoretical studies support empirical throwing research.

Bauer and Schöllhorn (1997) used 53 discus throws (45 of a decathlete, 8 of a specialist) recorded using semi-automated marker tracking over a one-year period of training. There were 34 kinematic time series for each throw, for 51 normalized times; these complex, multi-dimensional time series were mapped on to a simple 11×11 neuron output space (Figure 1). Each sequence was then expressed as the mean deviation (*d* in the figure) of the output map (the continuous line) from the output map of one of the throws by the specialist

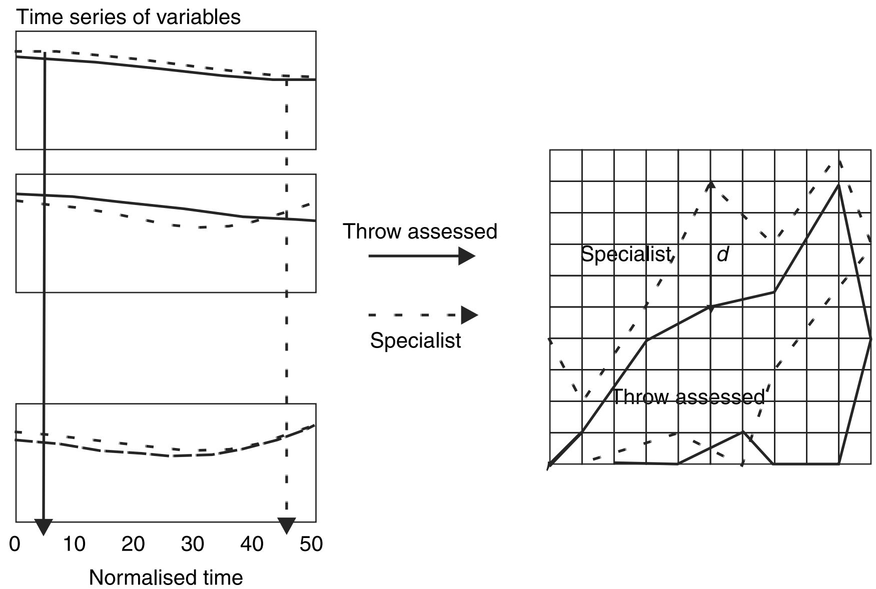

Figure 1. Mapping of input times series (on left) onto an 11 × 11 output matrix for the discus throw to be assessed (solid line) against the reference throw from the specialist thrower (adapted from Bauer and Schöllhorn, 1997).

thrower (the dashed line). It should be noted here that this distance between network nodes has no Euclidean significance, although the authors' calculations imply that it has; this might have affected their findings.

The deviations for the eight specialist throws are shown on the right of Figure 2 and the decathlete's 45 throws on the left. The "distances" are less for the specialist thrower as the comparator was one of his throws. Note the clustering of groups of throws, between the

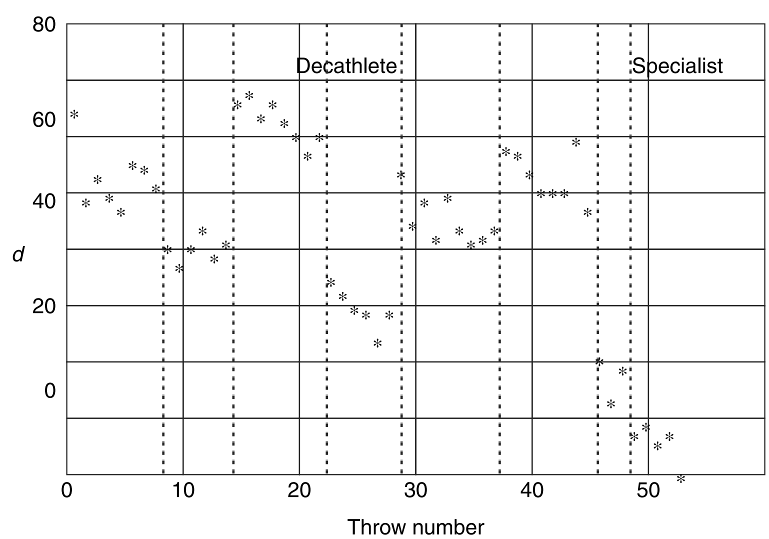

Figure 2. Values of the mean distance (*d*) for various throws show grouping within training or competition sessions, between the vertical lines (adapted from Bauer and Schöllhorn, 1997).

vertical lines, within training or competition sessions. There was more variability between than within sessions – for five groups of five trials, the authors computed inter- and intra-cluster variances, giving an inter-to-intra variance ratio of 3.3 ± 0.6. This shows that even elite throwers cannot reproduce invariant movement patterns between sessions. The supposed existence of such invariant patterns – which arose mainly from the motor program concept of cognitive motor control – has often been used, explicitly or implicitly, to justify the use of a "representative trial" in sports biomechanics; such trials clearly do not exist.

Schöllhorn and Bauer (1998) used a similar approach to analyse 49 javelin throws from eight elite males, nine elite females, and ten heptathletes. This time, manual digitizing of estimated joint centre locations was used. Clustering was found for the male throwers – as a group – and for the two females for whom multiple trials were recorded. Variations in the cluster for international male athletes were held again to contradict the existence of an "optimal movement pattern", even for "good" efforts.

Intra-individual coordination variability was reported for elite throwers in an empirical study by C. Morriss and colleagues (unpublished data). They studied four throws, all for maximum range, from the men's gold medallist at the 1996 Olympic Games, and presented the results as cross-correlation coefficients. The cross-correlations between the right shoulder and elbow joint angles of the throwing arm (Figure 3), for example, showed very similar patterns for rounds 2 and 6, and for rounds 4 and 5, within the limits of experimental error, as outlined below. The same was not true between the 2–6 and 4–5 pairs, which had substantial amplitude and phase differences (Figure 3). Bartlett, Müller, Lindinger, Brunner, and Morriss (1996) reported intra-individual differences in novice, club, and elite javelin throwers; although not reported explicitly in that paper, intra-individual differences were greater for the novice and elite throwers than for the club throwers. Even throwers striving for maximum distance cannot generate identical coordination patterns.

In the context of some of the above studies (Morriss et al., 1997; Schöllhorn and Bauer, 1998), the results of Bartlett, Bussey, and Flyger (2006) merit attention. They reported the results of a study of five trials of treadmill running in a laboratory to ascertain the reliability of

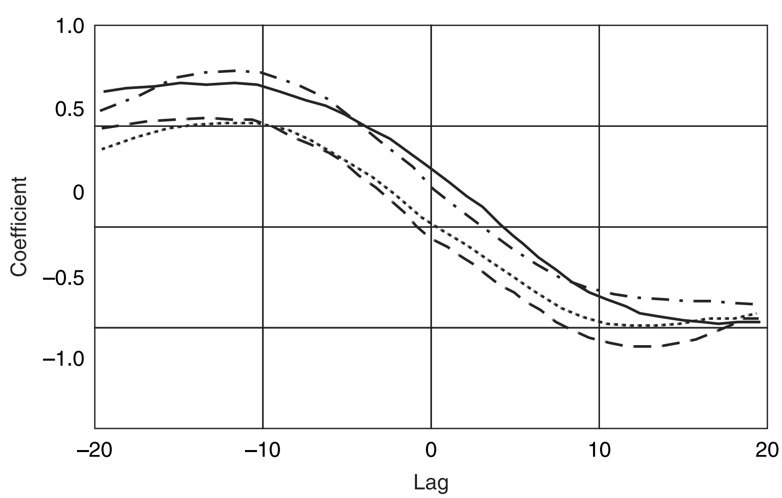

Figure 3. Cross-correlation functions at various phase lags between the throwing arm shoulder and elbow joints for four throws by the 1996 men's Olympic gold medallist (Rounds (R) as follows: continuous line = R2; dashed line = R4; chained dashed line = R5; dotted line = R6).

manual digitizing of body coordinates with and without markers; four experienced operators digitized the trails on each of five consecutive days, with the no-markers trials being digitized before the ones with markers, to inhibit learning of marker positions. In the marker trails, the intra- and inter-operator reliability was good (Figure 4a, c), with the former similar to autotracking; movement (trial-to-trial variability) dominated the other sources of variance. However, this was not true for the no-marker condition (Figure 4b, d), in which movement variability was often swamped by the other sources of variance. The authors concluded that movement variability could not be determined reliably without the use of markers and speculated that this would be even worse for three-dimensional studies in competition in which the positions of some "joint centres" have to be estimated from invisible landmarks. It is with those results in mind that the four trials in the study of Morriss and colleagues (unpublished data) have been divided into two pairs – the differences within each pair would fall inside the limits of such experimental errors.

A computer simulation model that could be considered to have predicted variability in sports movements was given in Best, Bartlett, and Sawyer (1995), who presented their results as contour maps of two variables. Figure 5 provides an example for the release angle of attack of the javelin against release angle, with other release parameters kept constant, as it is difficult to represent *n*-dimensional space in two dimensions. The contour lines are lines of equal distance thrown. The peak of the "hill", shown by the black circle, represents the maximum distance that a given thrower could throw a particular make of javelin. It should be noted that only one combination of release parameters gave the maximum throw. However,

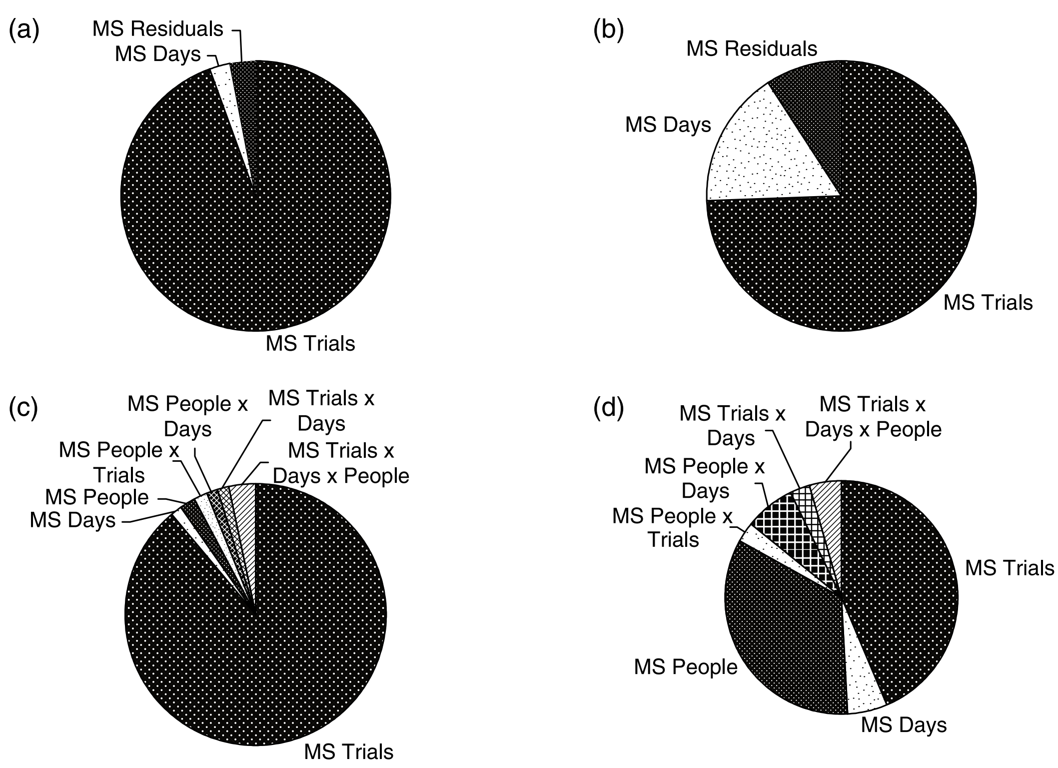

Figure 4. Partitioning of variability between its various sources: (a) typical operator with markers, (b) typical operator without markers, (c) group with markers, (d) group without markers (adapted from Bartlett et al., 2006).

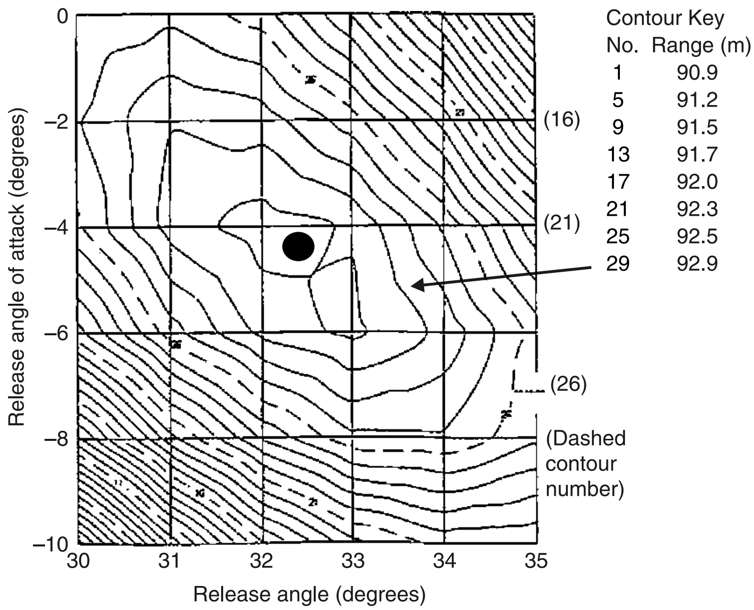

Figure 5. Contour map of simulated range thrown for different combinations of release angle and release angle of attack for the maximum release speed at which that thrower could throw and for a given model of javelin. Contours are lines of constant range (adapted from Best et al., 1995).

on any two-dimensional contour map, any pair of release parameters on a constant range line will produce that sub-optimal throw, even when the sub-optimal range is only slightly less than maximal, as for contour line 29 on Figure 6 indicated by the arrow; this generalizes to *n*-dimensional representations of the release parameters. These results show than infinite combinations of release parameters will result in the same sub-optimal range; each of these combinations could have arisen from kinematically different movements of the thrower. Furthermore, the unique maximal throw combination of release parameters could also have arisen from kinematically different motions that generated the optimal release parameter values (see Kudo, Ito, Tautsui, Yamamoto, and Ishikura, 2000). Outcome consistency does not require movement consistency.

These computer simulation results appear to predict "sub-optimal" movement variability. This variability in javelin throwing could be functional in allowing adaptations to environmental changes, such as wind conditions, or to distribute maximal loads on each throw among different tissues, both of which are discussed further below in the section on running. However, the functionality of such variability is still somewhat speculative.

Variability in basketball shooting

Shooting is the most important skill in basketball and many researchers have, consequently, studied this aspect of the game. Changes in basketball shooting kinematics have been examined as a function of distance (Elliott and White, 1989; Miller, 2002; Miller and Bartlett, 1996; Robins, Wheat, Irwin, and Bartlett, 2006), sex (Elliott, 1992), ability (Button, MacLeod, Sanders, and Coleman, 2003; Hudson, 1985; Penrose and Blanksby, 1976), and shooting accuracy (Miller, 1998). One of the general trends to emerge is that shooting is a compromise between the allowable margin for error and energy expenditure

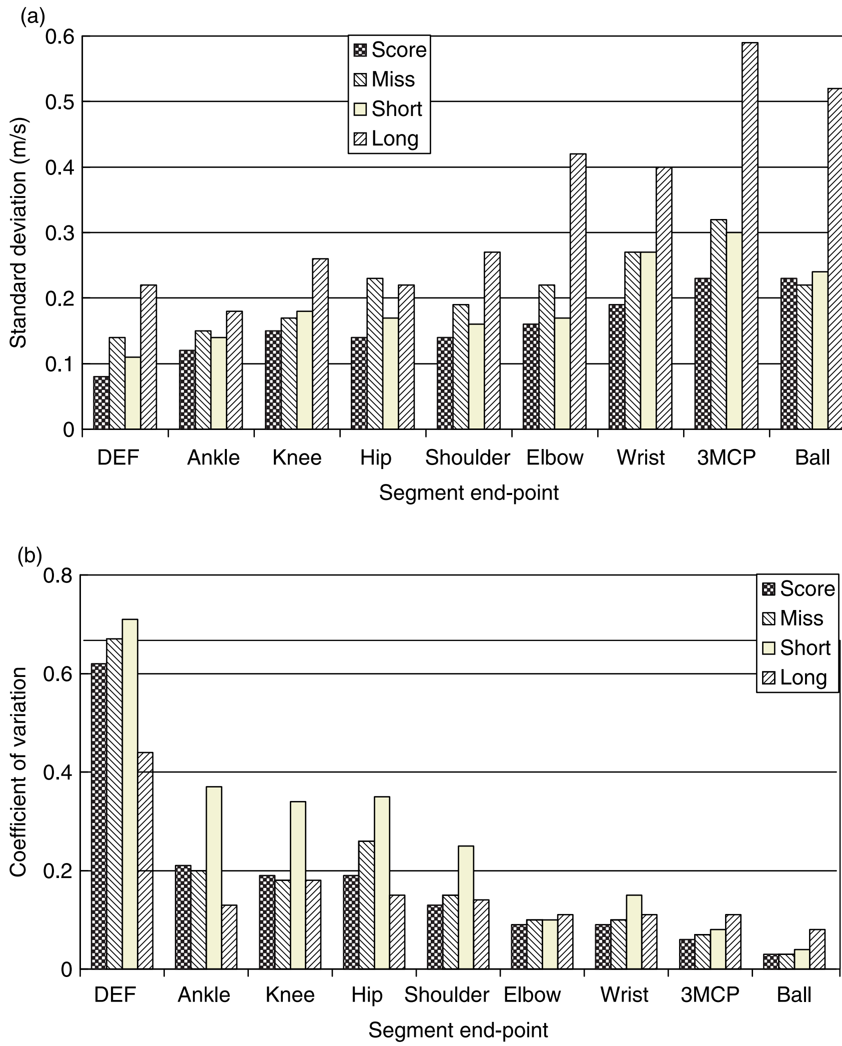

Figure 6. (a) Absolute variability, expressed as standard deviation, and (b) relative variability, expressed as coefficient of variation, in segment end-point speeds for the three successful throws – from the free-throw line (score), 2.74 m (short) and 6.4 m (long), and for unsuccessful throws from the free throw line (miss).

(see, for example, Miller and Bartlett, 1996). The joint configurations and release parameters used by players are, therefore, tailored to a particular shooting distance. For example, players use a shallower shooting trajectory at greater distances to reduce the required ball release speed (the minimum speed principle; see Miller and Bartlett, 1996). However, this produces a correspondingly lower margin for error because the basketball ring has a smaller elliptical area through which the ball can travel. The impact of these changing accuracy demands on measures of movement variability has rarely been addressed.

Movement variability in basketball shooting has received little attention until recently (Button et al., 2003; Miller, 2002; Robins et al., 2006). In a study by Miller (1998, 2002), 12 experienced basketball players each completed five successful and five not-deliberately unsuccessful shots at distances of 2.74, 4.23 (free-throw line), and 6.4 m. Measures of movement variability included coefficients of variation for ball release parameters, standard deviations for ranges of motion for the wrist, elbow and shoulder joints, and absolute and relative variability of segment end-point linear speeds at ball release. No evidence was found to suggest that the players could generate identical movements from shot to shot. There was increased absolute variability, expressed as standard deviation, in segment end-point speeds, from the longest to the shortest distances, which was reversed for relative variability, expressed by the coefficient of variation (Figure 6). No significant difference in absolute variability of joint position at release was found between successful and unsuccessful throws. For example, the standard deviation for range of motion in free throws for the wrist and elbow joints was 7.5° and 6.3° for accurate shots and 7.5° and 5.7° for inaccurate shots respectively. An increasing trend in absolute variability of segment end-point speed along the segment chain was also apparent, but a deceasing trend in relative variability (Figure 6).

Button et al. (2003) examined how movement variability in the basketball free-throw was affected by differing abilities among female players ranging from a senior national team captain and two under-18 national team players to a player of very little experience. Skilled performers were characterized by increased inter-trial consistency from the elbow and wrist joints, but no clear reduction in trajectory variability occurred as skill increased. Trajectory variability referred to the standard deviation of linear elbow displacement at discrete points during the throwing action. Of particular interest, the observed increase in the standard deviation of joint angle at ball release from the elbow to the wrist joint was proposed to act as a compensatory mechanism. This compensatory interaction of joints along the kinematic chain has been suggested to minimize the variability of release parameters. Compensatory variability has also been reported in other dynamic throwing tasks (Kudo et al., 2000; McDonald, van Emmerik, and Newell, 1989; Muller and Loosch, 1999). Finally, skilled players exhibited a greater range of wrist motion, but the authors did not allude to the potential importance of this finding from a coaching perspective.

Robins and co-workers (Robins, 2003; Robins et al., 2006) analysed five standardized, successful jump shots from each of six experienced basketball players. Shots were taken at distances of 4.25 m (free-throw line), 5.25 m, and 6.25 m (three-point line). Their findings suggested that all participants were capable of replicating the desired movement pattern at all three distances, and showed a narrow bandwidth of movement variability (see Figure 7). This narrow bandwidth of movement variability corroborates earlier research demonstrating a reduction in movement variability with practice in basketball (Button et al., 2003) and dart throwing (McDonald et al., 1989). Although, considering the premise of the paper, a reduction in movement variability as a function of practice appears paradoxical, there is evidence to suggest that experts can exploit the available movement variability functionally to satisfy the constraints of the task. Robins et al. (2006) found that movement variability at the shoulder and elbow did not increase as a function of distance; the wrist was the only joint with an increased variability of joint position at release. Standard deviations of 3.5°, 3.2°, and 2.2° were reported at ball release for the shoulder joint, for example, at distances of 4.25, 5.25, and 6.25 m respectively. This finding counters those reported by Miller (1998, 2002) and opposes the views proposed by impulse-variability theory (see Schmidt, Zelaznik, Hawkins, Frank, and Quinn, 1979).

Robins and colleagues (Robins, 2003; Robins et al., 2006) also observed an increase in the standard deviation of joint angle at ball release from the shoulder to the wrist joint. Furthermore, the variability of joint angles at release did not have an adverse effect on the height, angle or speed of release, suggesting that compensatory mechanisms were present at

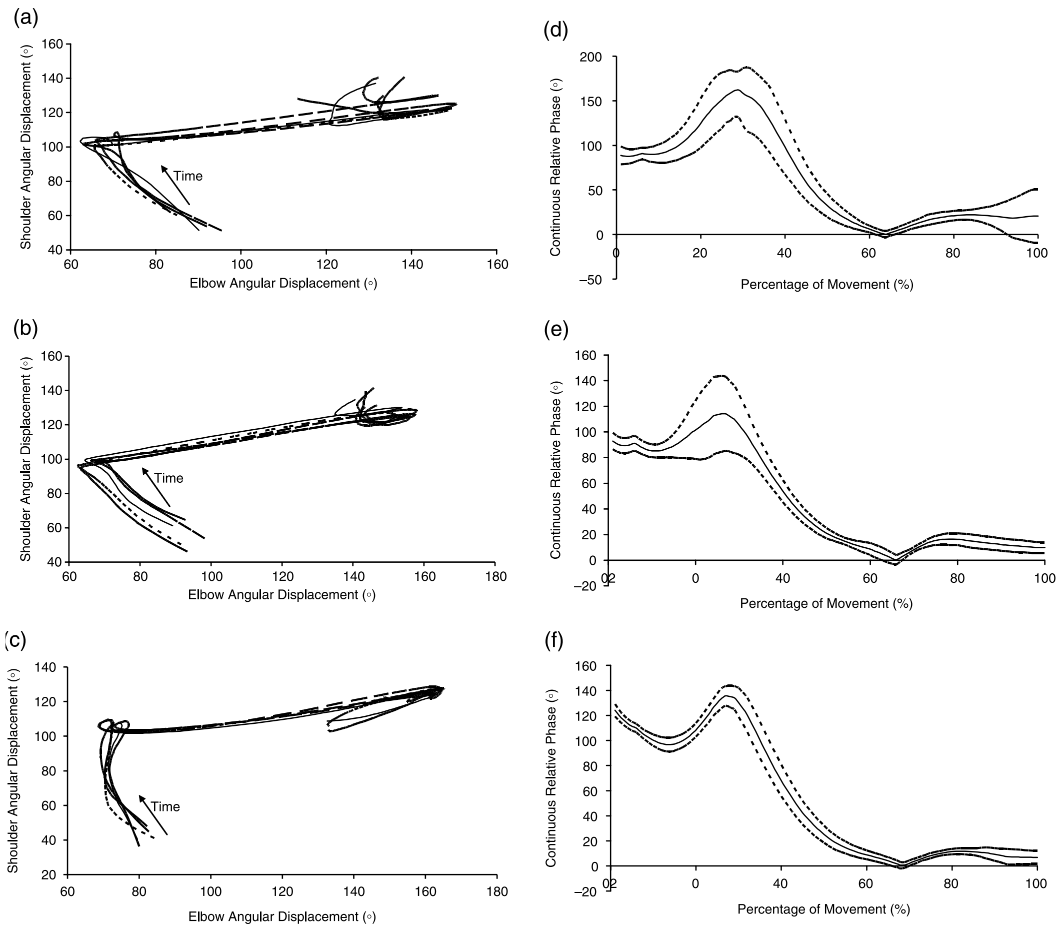

Figure 7. Changes in movement variability as a function of shooting distance (4.25, 5.25, and 6.25 m) for five trials for a typical player expressed as angle–angle diagrams for the sagittal plane coupling of the shoulder and elbow (a–c) and as continuous relative phase [CRP; shown as mean (continuous line) ± standard deviation (dashed lines)] between the same angles (d–f) (from Robins, 2003).

the wrist and elbow joints to minimize the variability of projectile release parameters, thus implying a more functional role for movement variability. Values for height, angle, and speed of release were delimited within 50 mm, 2°, and 0.7 m/s, respectively, regardless of shooting distance. This finding is in line with those of Button et al. (2003), and offers additional support for the theory of compensatory variability. This compensatory strategy might explain why the variability values for the height of release reported by both Button et al. (2003) and Robins et al. (2006) were relatively unchanged. Within a practical context, a reduction in shoulder extension could be corrected for by increased elbow extension. An elevated height of release, a commonly reinforced coaching point (Wissel, 1994), would, therefore, have the benefit of requiring a lower speed of release for a given release angle (Miller and Bartlett, 1996).

The freeing of biomechanical degrees of freedom, which occurs with motor learning (Vereijken, Whiting, Newell, and van Emmerik, 1992), may assist with the apparent compensatory strategy exhibited by skilled performers. Skilled performers have been shown to display more than twice the wrist flexion (82°) of unskilled performers (Button et al., 2003). An increase in wrist amplitude could serve several purposes. First, a larger range of motion at the wrist may be used in conjunction with an increase in vertical and horizontal displacement of the jump (Elliott, 1992) to assist with impulse generation. Also, exploring a fuller range of motion may enable a more effective compensatory mechanism to ensure end-point accuracy.

Although the analysis of discrete variables of interest yields important information at key instants, such as ball release, it is often necessary to supplement discrete measurements with continuous variables. The use of coordination profiling and, in particular, coordination variability, is often favoured by dynamical systems theorists and provides an invaluable insight into how individuals adapt to changing constraints. When assessing the effect of an increased shooting distance on coordination variability, Robins et al. (2006) reported a significant reduction in continuous coordination variability for the joint couplings of the wrist–elbow ($P = 0.01$) and wrist–shoulder ($P = 0.01$). Significant reductions were also observed for the variability of the joint couplings of the wrist–elbow ($P = 0.0001$), elbow–shoulder ($P = 0.07$), and wrist–shoulder ($P = 0.001$) at ball release. The decrease in both discrete and continuous measures of movement variability with distance can be attributed to the reduction in margin for error. A smaller margin for error at longer shooting distances requires a more constrained movement pattern, one that is characterized by lower movement variability. Therefore, it is feasible that the magnitude of variability is dependent on the constraints of the task (Newell and Vaillancourt, 2001).

The availability of equally functional movement patterns is important because it offers greater flexibility to adapt to potential perturbations and environmental uncertainty. This is particularly important during basketball competition because the extent of defender interference or pressure increases as players move closer to the basket. However, this flexibility is not available at greater distances, because the margin for error demands that the coordination pattern is more closely constrained. Coaches are, therefore, advised to devise strategies and play patterns that provide free scoring opportunities when shooting from the perimeter. This will minimize defender interference and prevent the shooter from having to manipulate his or her technique to any great extent.

Variability in locomotion

Sports biomechanists have investigated running mechanics with the aim either of enhancing performance (e.g. Saunders, Pyne, Telford, and Hawley, 2004) or, more frequently, of identifying biomechanical factors that might contribute to the causes of overuse injury (e.g. Hreljac, Marshall, & Hume, 2000; McClay and Manal, 1997; Stergiou, Bates, and James, 1999). Traditional approaches to the study of running mechanics have been greatly influenced by theories of the cognitive approach to movement control; consequently, biomechanical studies of running have tended to focus on identifying the invariant properties of human movement. Therefore, biomechanics researchers have consistently assumed that within- and between-runner variability is of little or no importance. Indeed, techniques for reducing and eliminating both within- and between-participants variability have been used frequently (e.g. Hunter, Marshall, and McNair, 2004; Mullineaux, Clayton, and Gnagey, 2004; Schwartz, Trost, and Wervey, 2004).

Another approach to movement coordination and control is based on non-linear dynamical systems theory (Hamill, van Emmerik, Heiderscheit, and Li, 1999), which is often referred to simply as dynamical systems theory, a practice we use in this paper, although the non-linearity of such systems is essential to their behaviour. This approach challenges traditional views of movement variability, which assume variability to be system noise or error that must be eliminated: dynamical systems theory, in contrast, proposes that variability is functional. Hamill et al. (1999) stated that a central message of research in motor control from a dynamical systems perspective (e.g. Schöner, Haken, and Kelso, 1986) is that variability in movement is necessary for changes in the coordination of movement, for example from walking to running or vice versa (Diedrich and Warren, 1995).

As well as assisting in coordination changes, various authors have postulated recently that another function of movement variability might be to attenuate impact shocks when runners are subjected to large forces (Hamill et al., 1999; Heiderscheit, Hamill, and van Emmerik, 1999, 2002; Holt, Jeng, Radcliffe, and Hamill, 1995; James, 2004; James, Dufek, and Bates, 2000). These authors suggested that variability in movement might provide a broader distribution of stresses among different tissues, potentially reducing the cumulative load on internal structures of the body. Furthermore, some experimental evidence exists (Hamill et al., 1999; Heiderscheit et al., 2002; James et al., 2000) to support the "variability-overuse injury hypothesis" (Figure 8). Because of the potential functional roles of movement variability, it would appear necessary to re-assess the solely non-functional views of variability.

Traditionally, dependent variables in studies of running biomechanics – as in the biomechanics of throwing skills in the previous two sections – have tended to be discrete data from isolated joints (e.g. Paradisis and Cooke, 2001). However, the dynamical systems approach advocates that the coordination or coupling between joints of the lower extremity is important. Running, like throwing, is a complex motor skill that involves many degrees of freedom. To produce coordinated movement and master the many interacting components in the human body, the runner must solve what Bernstein (1967) termed the "degrees of freedom problem". Recently, it has been recognized that, sometimes, analysing discrete variables from isolated joints does not effectively capture the complexity of the coordinated motions of components of the body. An excellent example of this during running is the coordinated actions of the subtalar and knee joints. Briefly, both knee flexion and subtalar eversion are associated with internal rotation of the tibia. Conversely, subtalar inversion and knee extension are associated with external rotation of the tibia. Therefore, it has been suggested that a disruption to the coordination between the subtalar and knee joints during the stance phase of running might create torsional stresses on the tibia and abnormal loads on the knee joint (e.g. DeLeo, Dierks, Ferber, and Davis, 2004; McClay and Manal, 1997;

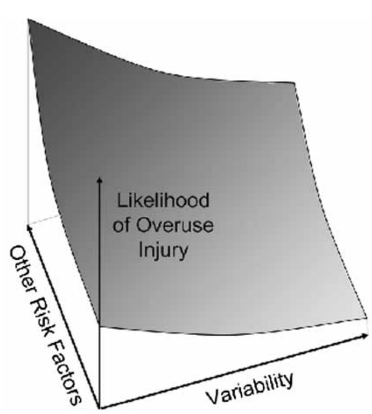

Figure 8. Hypothetical relationship between variability and the likelihood of overuse injury with a representation of the influence of other risk factors associated with overuse injury (from Wheat, 2005).

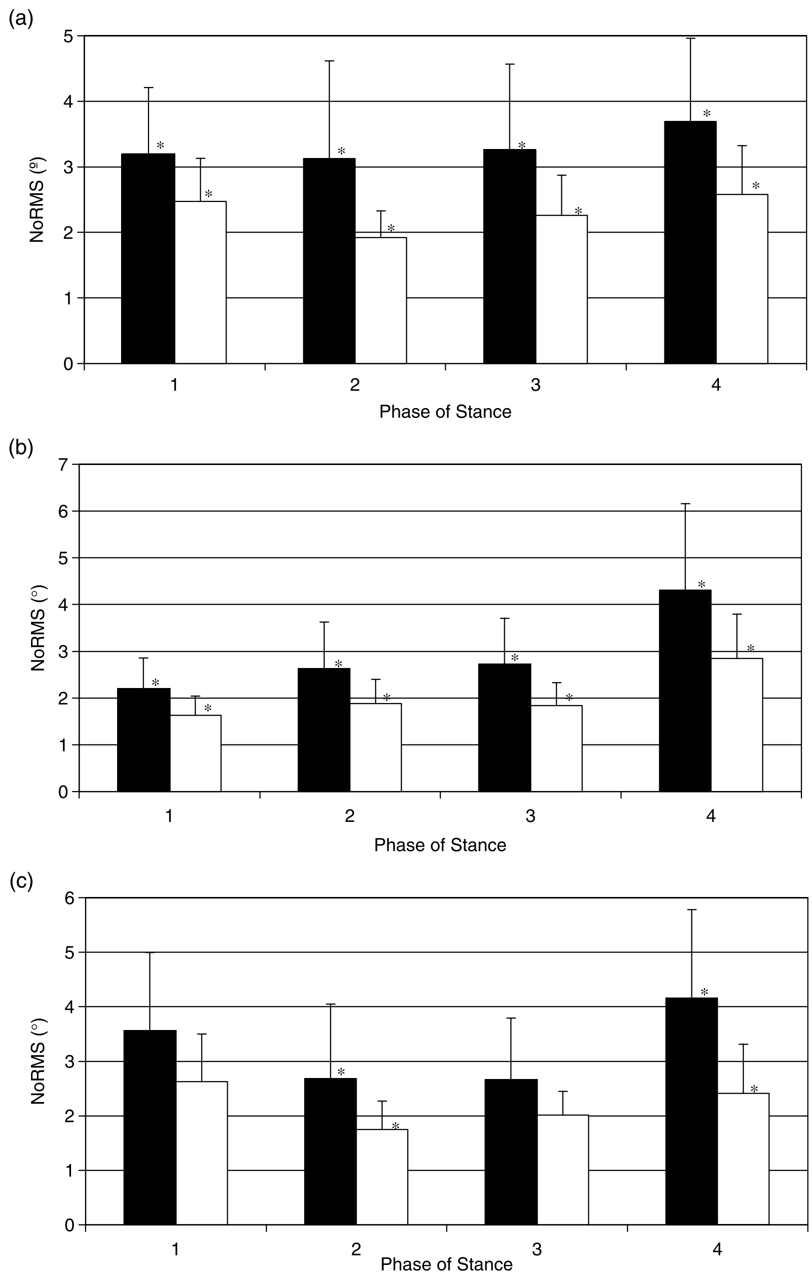

Figure 9. Average variability expressed as normalized root mean squared errors (NoRMS) in coordination patterns during treadmill (white) and overground (black) running for the joint couplings of (a) hip flexion–knee flexion, (b) hip flexion–ankle dorsiflexion, and (c) knee flexion–rear foot (subtalar joint) inversion over the four quarters of the stance phase, where phases 1, 2, 3, and 4 are 0–25%, 26–50%, 51–75%, and 76–100% of stance respectively. *Significant difference between conditions ($P < 0.05$) (data from Wheat, 2005).

Stergiou and Bates, 1997; Stergiou et al., 1999). With this in mind, investigating the actions of the subtalar and knee joints in isolation might omit important information about running injury mechanics.

Hamill et al. (1999) were among the first to use the dynamical systems approach to investigate overuse running injuries. They recognized the two important tenets of dynamical systems theory outlined previously in this section – the importance of movement variability and inter-segment coordination. Using a retrospective research design, they compared the variability in lower extremity coordination of participants with patellofemoral pain with a group of healthy, matched controls. Less variability in coordination was reported for the patellofemoral pain group than the control group (Hamill et al., 1999). Potentially, these results provide support for the hypothesized link between variability and overuse injury. Follow-up studies (Heiderscheit, 2000; Heiderscheit et al., 2002) reported similar results to Hamill et al. (1999). However, with the retrospective research designs used in these studies, it is impossible to determine whether the decreased variability was the cause or the effect of the patellofemoral pain.

In addition to the possibility that lower variability caused the injury, it is just as plausible that the decreased variability seen in the injured participants was the result of pain (Hamill et al., 1999; Heiderscheit, 2000; Heiderscheit et al., 2002). Hamill et al. (1999) suggested that the decreased variability in coordination seen in the patellofemoral pain group could have been a result of the participants constraining their movements within tight boundaries inside which pain was reduced. Heiderscheit (2000) presented preliminary findings that provide support for this notion. He monitored variability in coordination after reduction in pain owing to the application of patella taping, and found that variability in the coordination patterns in the injured group increased to near that of the healthy group after reduction in pain.

The findings of Hamill et al. (1999), Heiderscheit (2000), and Heiderscheit et al. (2002), together with the results presented by James et al. (2000), have demonstrated a potential relationship between variability and overuse injury. As many authors have highlighted, more work is required to determine whether the decreased variability seen in injured participants is the cause or the effect of the injury. Specifically, work is required to confirm or refute the variability-overuse injury hypothesis presented by James (2004).

A third functional role for movement variability is that of facilitating adaptation to changes in the environment, as previously mentioned for javelin throwing. Wheat and his colleagues (Wheat, 2005; Wheat, Baltzopoulos, Milner, Bartlett, and Tsaupolos, 2005) have reported comparisons of running overground, on a standard treadmill and on an on-demand treadmill, in which the belt speed adapts to the speed of the runner (Minetti, Boldrini, Brusamlin, Zamparo, and McKee, 2003).

Between the overground and treadmill conditions, for 11 male runners, Wheat (2005) reported significantly reduced variability in lower extremity coordination ($P < 0.05$) on the treadmill than in the overground condition for all joint couplings studied (Figure 9). These results were in agreement with data on the variability in the vertical velocity of the centre of mass during running (Wank, Frick, and Schmidtbleicher, 1998) and variability in lower extremity kinematics during walking (Dingwell, Cusumano, Cavanagh, and Sternad, 2001). The results also lent some support to the hypothesis of Holt et al. (1995) that variability in coordination patterns might provide an adaptive mechanism to potential external perturbations, such as uneven ground. However, as Wheat (2005) noted, the reduced variability in treadmill running could have other causes. Potential reasons for the differences include, for example, intra-stride belt speed variations, changes in air resistance, and changes in optical flow information.

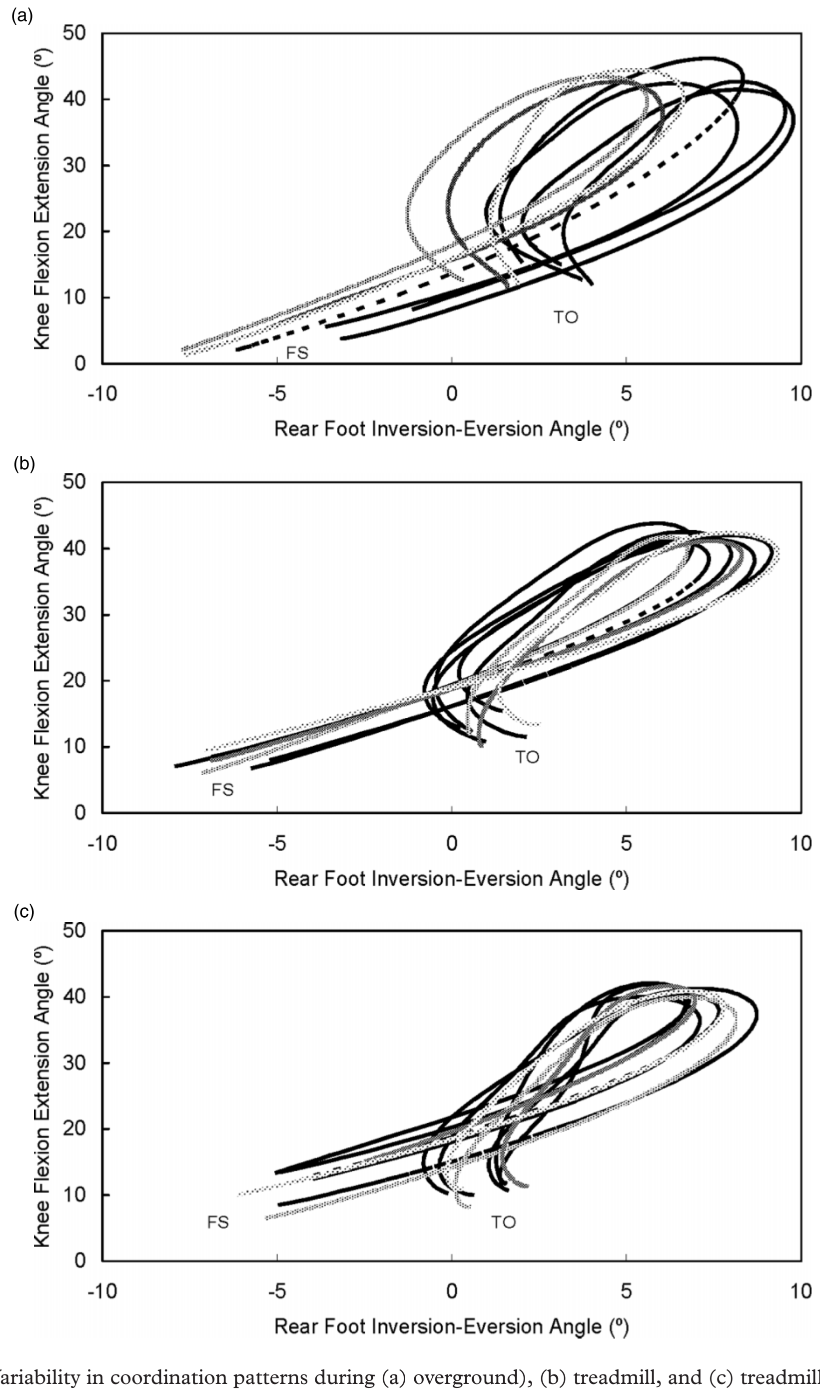

Figure 10. Variability in coordination patterns during (a) overground), (b) treadmill, and (c) treadmill-on-demand running for the joint coupling of knee flexion–extension and rear foot (subtalar joint) inversion–eversion for the eight trials of a typical participant. FS = foot strike, TO = toe-off (from Wheat, 2005).

It is also possible that, as Dingwell et al. (2001) suggested, the reduced variability seen during treadmill locomotion could be due to the artificially constant speed of the treadmill belt. However, Wheat (2005) reported similar differences in variability (Figures 10 and 11) between running overground and on a treadmill, and between running overground and on a treadmill-on-demand – on which the treadmill belt speed was not constant (effect sizes of 0.84–1.71 and 0.94–1.95, respectively). Furthermore, no differences were reported between the two treadmill conditions (effect sizes < 0.41). The constant speed of the treadmill belt on a conventional treadmill does not appear, therefore, to account for the reductions in variability observed between treadmill and overground conditions. At present, it is unclear which other factors are responsible for the differences. We would speculate that the suggestion of Holt et al. (1995) of an adaptive mechanism to potential external perturbations, of which there is a lesser threat on a treadmill, and the reduction of optical flow information on a treadmill are strong candidates to explain the differences between treadmill and overground movement variabilities.

Summary and implications

None of the research discussed above (which is, admittedly, not comprehensive) supports the concepts of intra-individual movement consistency or motor invariance. Even elite athletes appear unable to produce invariant movement patterns after years of practice (Davids et al., 2003). Such research also militates against the concepts of inter-individual optimal movement patterns and "representative" trials. It also argues very strongly for within-individual studies to supplement group designs.

Different motor control paradigms have different views of variability. Cognitive motor control theorists traditionally considered variability as undesirable system noise, or error, and saw variability as reducing with skill learning as the learner freezes unwanted degrees of freedom in the kinematic chain. Ecological motor control specialists view variability as having a functional role in human movement. Variability is seen as essential in inducing a coordination change and it gives flexibility to adapt effectively to changes in the environment. This motor control group sees skill learning and practice as an exploration of the "perceptual-motor workspace" (see, for example, Handford, Davids, Bennett, and Button, 1997).

In our view, sports biomechanists have not, until recently, shown enough interest in movement variability. Several sports biomechanics research groups, as noted above, have already started to rectify this omission. What this involvement has already added to existing knowledge is a third possible functional role for variability. If movements were repeated identically, it is more likely that the same tissues would be maximally loaded each time. Adding in movement variability probably modifies tissue loads from repetition to repetition, reducing injury risk. This remains hypothetical at present.

Sports biomechanists should also be able to provide a greater insight into variability in multi-segment movements. Single-segment or single degree-of-freedom joint rotations have dominated those investigated by the cognitive school of motor control, and much of the early work of the ecological school – although both have turned their attention to real-world tasks, such as sport. In contrast to these simple movements, in multi-segmental movements inertial coupling (Putnam, 1983) might cause variability "transfer" between segments; furthermore, muscles contribute to forces and moments at joints other than those they span, further complicating our understanding of movement variability (see, for example, Zajac and Gordon, 1989).

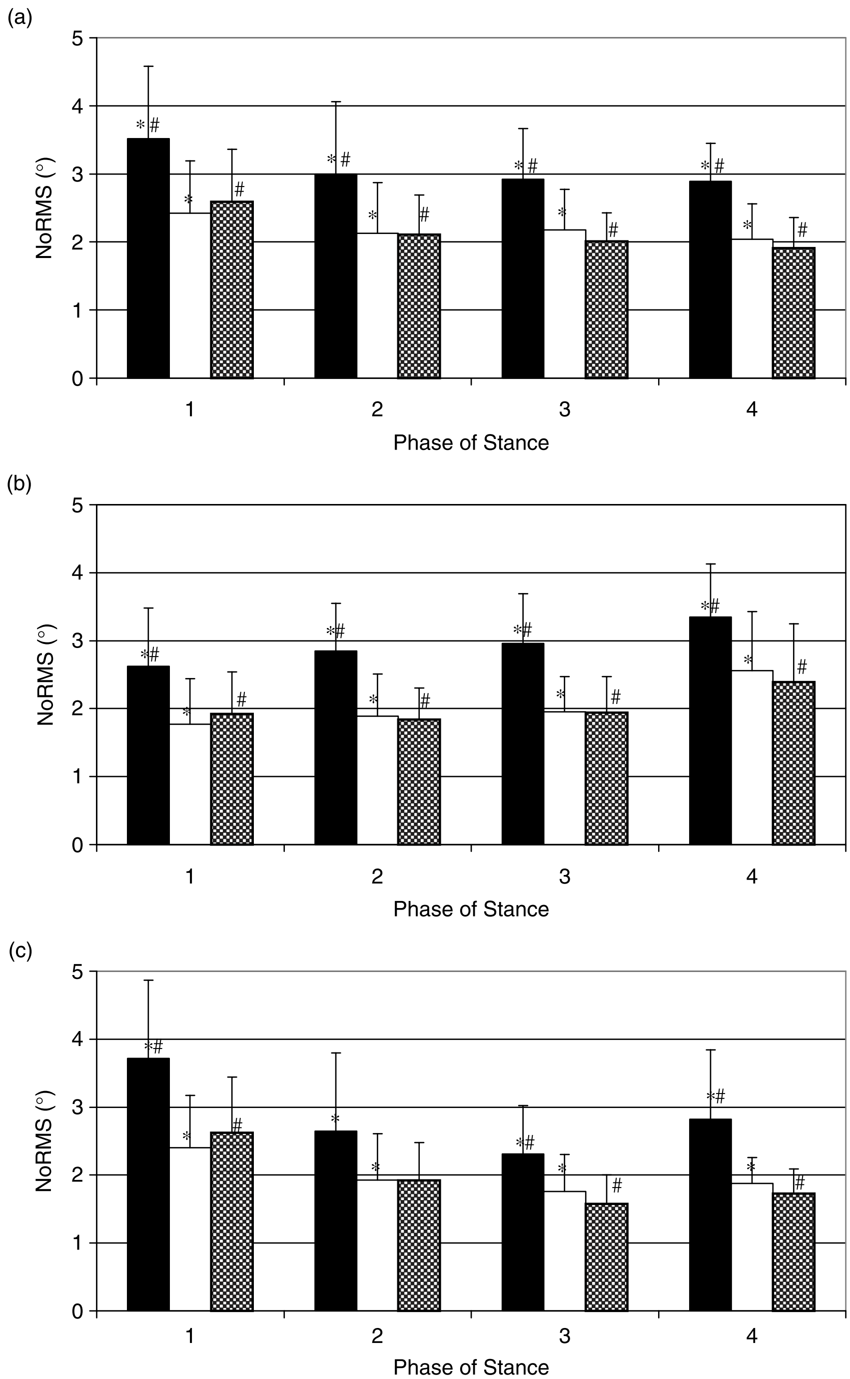

Figure 11. Average coordination variability expressed as normalized root mean squared errors (NoRMS) during treadmill (white), treadmill-on-demand (shaded), and overground (black) running for the joint couplings of (a) hip flexion–knee flexion, (b) hip flexion–ankle dorsiflexion, and (c) knee flexion–rear foot inversion over the four quarters of the stance phase, where phases 1, 2, 3, and 4 are 0–25%, 26–50%, 51–75%, and 76–100% of stance respectively. *Significant difference between overground and treadmill ($P < 0.05$). #Significant difference between overground and treadmill-on-demand conditions ($P < 0.05$) (data from Wheat, 2005).

Sports biomechanists are increasingly participating in the multi-disciplinary effort to understand movement control and coordination and the role of variability within that. One potential avenue that still requires exploration is that of artificial neural networks. Artificial neural nets can map very many input time series onto a simple output matrix, vastly reducing complexity; however, the uses of this in studying movement coordination and variability are still largely under-researched.

Many sports biomechanists, the lead author certainly among them, have made assumptions that research in movement variability seriously questions. We should accept that movement variability is crucially important for sports biomechanics and address the challenges it poses. So, how should sports biomechanics respond to the issues raised by movement variability, as well as the related topics of movement control and coordination, and the implications for practice and skill learning?

- We should carry out more collaborative research with specialists in motor control, motor learning, and motor development into the control and coordination of sports movements.
- We require inter-disciplinary studies of skills that require adaptation to environmental or task constraints, or that pose a threat of injury – an organismic constraint – or none of these, to tease out the relative importance of various sources of noise and functionality in movement variability.
- We need to investigate movement and coordination variability while individuals are learning a skill.
- We should place far more emphasis in sports biomechanics on intra-individual studies, generally as multiple single-individual designs, to address issues such as individual "signatures" of movement coordination and optimization of performance, rather than group designs that obscure important information.
- We need injury-focused studies of other sports movements, in addition to running, to establish if variability in segment coordination might indicate a function to prevent injury.
- We need longitudinal studies of specific sports movements to determine if individuals with low movement variability sustain more or less injuries that those with high variability. We also need to study how injury affects variability in the post-injury, treatment, and rehabilitation phases.

Finally, if movement variability is ubiquitous across sports, as we have shown in this review for javelin throwing, a speed-dominated skill, basketball shooting, in which there is a speed–accuracy trade-off, and running, a cyclic movement pattern, and across stages of skill acquisition, what does this imply for the sports practitioner? This is, perhaps, a question to be directed more at motor skills specialists than biomechanists, but we offer some views based on the research reviewed above.

- As different athletes perform the same task, such as a javelin throw, in different ways, there is no optimal movement pattern to achieve that task for athletes as a whole. Therefore, it makes no sense to try to copy specific details of a successful athlete's technique.
- These differences in movements between athletes have important implications for their physical training. The training exercises performed by each athlete should be done in a way that replicates their individual movement patterns, to ensure movement specificity.
- Because athletes do not replicate a movement exactly from trial to trial, for example in

basketball shooting, then the use of many trials in training needs to be carefully weighed against potential risks of overuse injury, particularly in activities in which loads on tissues are large, as in javelin throwing.

- As there is probably no unique movement that optimizes the performance of a given sports task, it makes sense to allow athletes, particularly in the early stages of learning, to explore possible solutions, rather then for the coach to impose too many unnecessary constraints upon them.
- We mentioned in the section on basketball that the availability of equally functional outcomes is important because it offers greater flexibility to adapt to environmental uncertainty. This is clearly important in competition in many invasive team sports, because the defender interference or pressure often increases as players move closer to the "target", be that the goal, try line, basket or whatever. However, this flexibility is not available at greater distances, because the margin for error demands that the coordination pattern is more closely constrained. Coaches are, therefore, advised to devise training strategies that provide free scoring opportunities from different distances from the target.

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